The Russian-American Gallium Experiment

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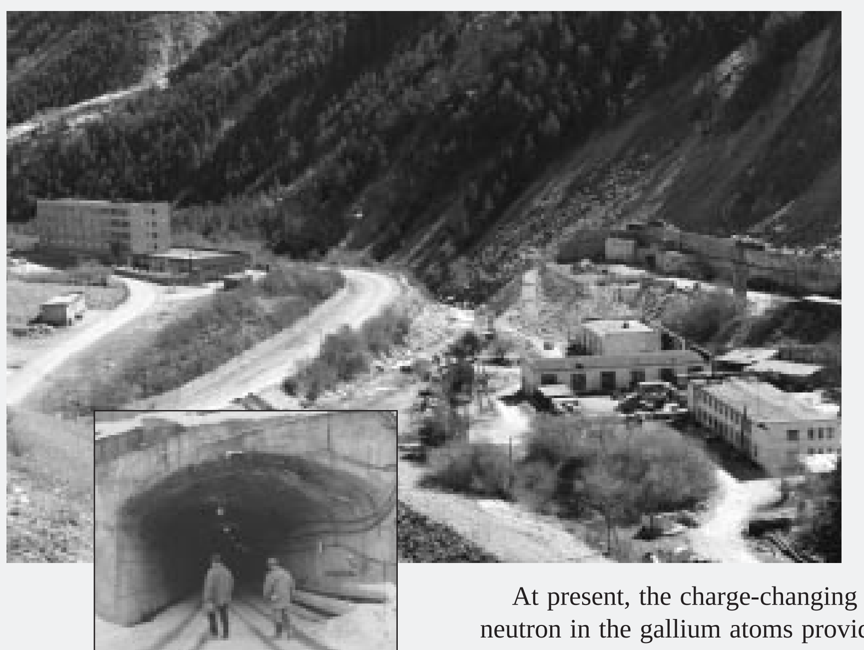
he Soviet-American gallium experiment AGE) was renamed the Russian-American allium experiment after the breakup of the oviet Union. Los Alamos has served as the ad U.S. laboratory for the experiment, with e University of Washington, the University Pennsylvania, Princeton University, and ouisiana State University rounding out the .S. side of the collaboration.

Beginning life as seepage from the snow-covered slopes of Mount Elbrus, the Baksan River gradually gains momentum as it ambles slowly northwest through the rugged Caucacus Mountains. Eventually, the river rumbles past the august face of Mount Andyrchi and the incongruous cluster of buildings, homes, and shops at its base known as Neutrino Village. The Baksan Neutrino Observatory is tucked into the mountainside under about 1.6 kilometers of hard rock. About 1,000 scientists, engineers, and families are tucked into the village.

The neutrino observatory is the result of some ambitious planning on the part of Soviet scientists. In 1964, the scientists dreamed of building several large detectors dedicated to observing the evasive neutrinos that streamed unfettered through the planet. Soon, they realized that burying the experiments under tons of rock would reduce the effects of cosmic rays. The rock itself would have to be geologically stable and relatively immune to earthquakes and other natural disasters. With an eye toward saving money, the scientists thought of digging a horizontal tunnel into a steep mountain. Equipment could then be hauled around by rail rather than up and down in mineshaft elevators. The Baksan River Valley in southern Russia presented itself as the ideal site. Years later, the Institute for Nuclear Research of the Russian Academy of Sciences would build Neutrino Village for the sole purpose of accommodating the needs of the Baksan Neutrino Observatory.



eutrino Village lies at the base of ount Andyrchi in the northern aucacus Mountains. The Russians ored about 3.5 kilometers straight to the mountain in order to bury AGE under tons of rock, and thus a esearcher's access to the experiment egins with a journey through darkness.

The SAGE experiment is the largest research effort at Baksan. Initiated in 1985 as a collaborative effort between the United States and the former Soviet Union, the experiment was designed to measure the flux of *pp* neutrinos that are produced in the dominant energy-producing mechanism of the sun. That particular flux is directly tied to the measured solar luminosity and is essentially independent of solar models. Hence, observation of a significant deficit of *pp* neutrinos would strongly suggest that a resolution to the solar-neutrino problem lies in the properties of the neutrino, rather than in solar physics.

At present, the charge-changing interaction between electron neutrinos and a neutron in the gallium atoms provides the only feasible means to measure the low-energy *pp* neutrinos. The reaction transforms a stable gallium atom into a radioactive isotope of germanium:

$$\nu_e + {}^{71}\mathrm{Ga} \rightarrow {}^{71}\mathrm{Ge} + e^- \ .$$

Because the unstable germanium atoms decay with a characteristic spectrum, they can be detected and their numbers counted. In this way, the solar-neutrino flux can be measured, and with a threshold of only 0.233 MeV, the reaction is sensitive to nearly the entire energy spectrum of solar neutrinos. In particular,

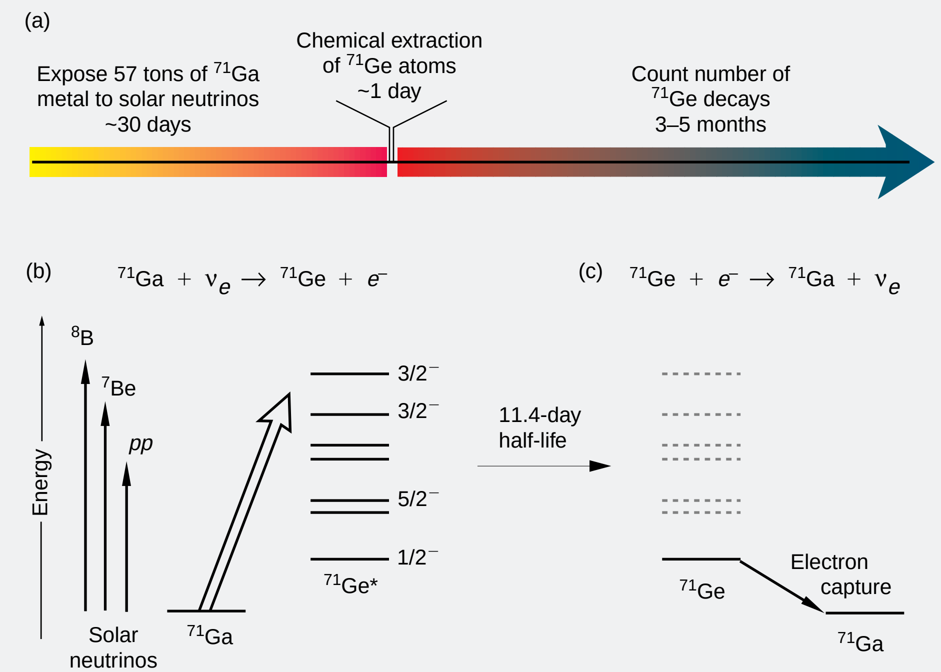


Figure 1. SAGE Overview
(a) SAGE has three distinct stages of operation: the transmutation of ^{71}Ga into unstable ^{71}Ge caused by solar neutrinos, the chemical extraction of the ^{71}Ge atoms, and the detection of the ^{71}Ge decays. The number of decays is proportional to the solar-neutrino flux.
(b) Because of low-lying excited states in the ^{71}Ge nucleus, the inverse-beta-decay reaction of gallium into germanium has a threshold of only 0.233 MeV. The reaction is therefore sensitive to *pp* and all other solar neutrinos. The energetic neutrinos leave the ^{71}Ge in an excited state, which quickly decays to the ground state.
(c) After an 11.4-day half-life, ^{71}Ge decays by capturing an orbital electron. The remaining electrons quickly reconfigure themselves around the new nucleus and dissipate excess energy by emitting x-rays and/or Auger electrons. These emissions are the signature of the decay.

54 percent of the detected signal should be due to neutrinos from the *pp* reaction, based on the predictions of the standard solar model for the total solar-neutrino flux.

In addition to SAGE, GALLEX (another international collaboration headed by MPIK Heidelberg) exploits the above reaction. The composition of the gallium target differs between the two experiments. SAGE uses metallic gallium (which becomes a liquid at just above room temperature), while GALLEX uses gallium in a liquid-chloride form. The different forms of the gallium are susceptible to very different types of backgrounds, and thus the two experiments provide a check for each other. This feature helps ensure that the observed events are due to reactions of solar neutrinos on gallium, rather than some background process.

Unlike other solar-neutrino detectors, the SAGE detector has a size that is of a conceptually manageable scale. The experiment initially employed about 30 tons of liquid gallium metal distributed among 4 tanks, each the size of a small hot tub. Today, the detector contains 57 tons of liquid metal distributed among 8 tanks. The Russians provided the gallium, valued at $40 million, in addition to the chemical extraction equipment, underground laboratory, and counting and analysis facilities. The Americans provided numerous pieces of equipment, including the primary counting system. The Americans also brought to the collaboration their substantial expertise in techniques for low-level counting. The Russians were responsible for operations, but both sides participated in data collection and analysis, as well as in publication of results.

SAGE indirectly measures the solar-neutrino flux by extracting and counting the germanium atoms produced in the gallium tanks. (See Figure 1.) About once a month, a chemical extraction is performed in which individual germanium-71 (^{71}Ge) atoms are plucked from among some 5×10^{29} gallium atoms. (Only 1.2 ^{71}Ge atoms are predicted to be produced per day in 30 tons of gallium, assuming the neutrino flux predicted by the standard solar model. The efficiency of the chemical extraction is simply incredible.) Just before the extraction, about 700 micrograms of stable germanium is added to the tanks. Monitoring the recovery of this natural germanium allows a measurement of the extraction efficiency for each run. The total germanium extract is purified and synthesized into germane (GeH_4), a measured quantity of xenon is added, and the mixture is inserted into a small-volume proportional counter.

The last bit of extract containing the unstable germanium is drawn out from the gallium tank. The extract appears as a silvery pool floating on top of the duller, liquid gallium metal.

The counter is then sealed and placed in the well of a sodium iodide (NaI) detector (used as a veto), which sits inside a large, passive shield.

Germanium-71 decays with an 11.4-day half-life to gallium-71 (^{71}Ga) by electron capture, in which an orbital electron in the ^{71}Ge atom is captured by a proton in the ^{71}Ge nucleus. The nucleus is converted to ^{71}Ga, but the decay also leaves the gallium atom in an excited state. The excess energy is carried off by low-energy electrons (Auger electrons) and by x-rays produced during the electron-shell relaxation of the ^{71}Ga atom. Taken together, the electron spectrum and the x-rays make for a characteristic decay signature. Pulse-shape discrimination and a maximum-likelihood analysis identify and distinguish that signature from all the other background signals detected by the proportional counter. The number of decays occurring over 4 to 6 months is recorded.

he tops of eight greenish tanks poke hrough the elevated floor of the Bak- an Neutrino Observatory. The squat nks contain a total of 57 tons of trapure gallium. Heating the tanks o about 30 degrees centigrade keeps he gallium in liquid form. Once or wice a day, one of the hundred tril- on or so solar neutrinos that pass hrough the tanks each second inter- cts with the gallium and produces n unstable germanium atom. These nstable atoms are extracted from the nks once a month. The red motors een perched above each tank are sed to rapidly stir the liquid gallium uring the extraction runs. The equip- ent seen in the foreground handles he chemicals used for the extraction. he red room to the left of the picture ouses all the electronics and control ystems used in the experiment.

Taking into account all efficiencies, the team expects SAGE to detect only about eight of the ^{71}Ge atoms produced in the 57 tons of gallium per run. Clearly, the backgrounds must be kept to a small fraction of a count per day. To yield such low backgrounds, the counters are made of specially selected quartz and zone-refined iron. All the components used in the NaI detector were specially selected; even the individual nuts and screws were measured for possible trace radioactivity.

The experiment began operation in May 1988 with the purification of 30 tons of gallium. Large quantities of long-lived ^{68}Ge (half-life = 271 days) had to be removed. They had been produced by cosmic rays while the gallium was on the earth's surface. By January 1990, the backgrounds had been reduced to sufficiently low levels that solar-neutrino measurements could begin. Since that time, extraction runs have been carried out monthly except for periods dedicated to calibration runs. SAGE reports the measured value of the solar-neutrino capture rate on ^{71}Ga to be

$$^{71}\text{Ga capture rate} = 72\ ^{+12}_{-10}\ \text{(statistical)}\ ^{+5}_{-7}\ \text{(systematic) SNU}\ .$$

An SNU (solar-neutrino unit) is equal to 10^{-36} captures per atom per second. This unit facilitates the comparison of results between different radiochemical experiments. The SAGE result is in excellent agreement with the GALLEX measurement of 70 ± 8 SNU. The capture rate predicted by the solar model was 132 ± 7 SNU, or nearly a factor of 2 higher.

Because SAGE observed a low signal compared with the solar-model prediction, the experiment underwent thorough checking to ensure it was working correctly. Much of the attention focused on the germanium-extraction procedure. The first test consisted of extracting stable germanium doped with a known number of radioactive ^{71}Ge atoms from 7 tons of gallium. The results indicated an extraction efficiency of 101 ± 5 percent for the natural germanium and 99 +6/ −8 percent for ^{71}Ge.

The definitive test of the extraction, however, was performed in 1995. The experiment used an extremely intense, artificial neutrino source to produce ^{71}Ge inside the detector. Chromium-51 (^{51}Cr) decays with a 27.7-day half-life by electron capture, thereby producing monoenergetic neutrinos. By placing a source containing 0.52 megacurie of ^{51}Cr inside 13 tons of gallium, one could expect to produce 50 times more ^{71}Ge atoms than the solar neutrinos would produce and anticipate to extract and observe about 147 atoms.

Half a million curies of anything is not to be treated lightly. The neutrinos

themselves are harmless, but about 10 percent of the time, ^{51}Cr decays by emitting a 320-kilo-electron-volt gamma ray. Left unshielded, those gammas would make the source a deadly menace. (Anyone holding the source, which is as small as a Coke can, would be fatally irradiated in about 1 minute.) The source was made in a fast breeder reactor in Kazakhstan. That reactor had been formerly used for plutonium production. A special assembly inserted into the reactor core was used for producing ^{51}Cr from highly enriched ^{50}Cr rods. The source was shielded by being placed inside a tungsten container with walls that were about 1 inch thick. All but about 0.001 percent of the gamma rays were absorbed in the shielding. The container radiated heat like a 100-watt light bulb.

Shielded in this manner, the source was perfectly safe to transport. But getting it into Russia turned out to be a problem. All arrangements for bringing the source in had been worked out when Kazakhstan was part of the Soviet Union, but by the time the source was to be delivered, Kazakhstan had become a separate country! The American team stood around, extremely unhappy, as 15 percent of the activity decayed away while the source sat in Russian customs for six days. A remarkable navigation of diplomatic channels finally led to a meeting, on Christmas day, between the SAGE members and the President of the Kabardino-Balkarya Academy of Sciences. Approval to transport the source to Baksan was finally granted. The result of the calibration experiment showed that the extraction and counting efficiencies were 95 ± 12 percent of those expected. The experiment was indeed working correctly. Thus, the observed deficit of solar neutrinos in SAGE is not due to some experimental error. Instead, it reflects a real deficit in neutrinos coming from the Sun.

Five members of the SAGE research team (the five people on the left) pose in front of the tunnel entrance. From left to right: Tanya Knodel, Ray Davis, Jr., Ken Kande, Vladimir Gavrin, and George Zatsepin. Also shown (continuing from left to right) are George Cowan, Igor Barabanov, and Keith Rowley.

The problem is now one of understanding the reason for the deficit. Unfortunately, SAGE cannot answer that question directly. The detection method can only infer the number of neutrino events that occurred in the gallium tanks. There is no way to extract information about the neutrino energy and, hence, about the shape of the solar-neutrino spectrum. The SAGE result, however, taken together with the results of other solar-neutrino experiments and the predictions of the standard solar model for the flux, suggests that the low-energy *pp* neutrinos are present in full strength while the flux of other, higher-energy solar neutrinos is significantly reduced. Many authors argue that these results cannot be reconciled with an astrophysical explanation. New experiments such as SNO are required for determining the origin of the solar-neutrino problem in a model-independent manner.

We hope that SAGE can continue measurements for a few more years. We are also investigating the possibility of converting gallium metal into gallium arsinide, which would enable construction of a real-time electronic detector for the entire solar-neutrino spectrum with very good energy resolution (a few kilo-electron-volts). The feasibility of such a detector still needs to be researched. However, the fate of the gallium, which remains the property of the Russian government, is now in doubt. Recently, an edict was issued requiring that the Institute for Nuclear Research of the Russian Academy of Sciences, which oversees the Baksan Observatory, return the gallium so that it could be sold and thus help pay salaries for unpaid government workers. While being sympathetic to the plight of the Russian workers, we also feel that, given its extremely high purity and low levels of trace radioactivity, the gallium should be considered a world resource to be invested in future research. We hope the Russian government will reach the same conclusion and explore other means to ease its fiscal crisis. ■