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TITLE: THE SOVIET-AMERICAN GALLIUM EXPERIMENT AT BAKSAN: A STATUS REPORT

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The Soviet-American Gallium Experiment at Baksan
A Status Report:

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Abstract

A gallium solar neutrino detector is sensitive to the full range of the solar neutrino spectrum, including the low-energy neutrinos from the fundamental proton-proton fusion reaction. If neutrino oscillations in the solar interior are responsible for the suppressed ^{8}B flux measured by the Homestake ^{37}Cl experiment and the Kamiokande water Cherenkov detector, then a comparison of the gallium, chlorine, and water results may make possible a determination of the neutrino mass difference and mixing angle. A 30-ton gallium detector is currently operating in the Baksan laboratory in the Soviet Union, with a ratio of expected solar signal to measured background (during the first one to two ^{71}Ge half lives) of approximately one.

1. Introduction

The discrepancy between the solar neutrino capture rate predicted by standard solar model calculations [1-4] and the ^{37}Ar rate measured by the chlorine experiment in the Homestake Gold Mine [5,6] (corroborated now by the Kamiokande II water Cherenkov results [7] has persisted for eighteen years. Recent calculated values are in the range 6-8 SNU (1 solar neutrino unit = 10^{-36} captures/target atom/sec), while the measured average $\nu_e + {}^{37}\mathrm{Cl} \rightarrow {}^{37}\mathrm{Ar} + e^-$ production rate is 2.3 +/- 0.3 SNU. In addition, recent analysis of the chlorine experiment suggests the possibility of time variations correlated with the 11 year solar cycle.[8]

The flux of the high-energy ^8B neutrinos (to which the chlorine and water experiments are most sensitive) is critically dependent on the temperature of the sun's core. Numerous nonstandard solar models[9] have therefore been suggested to account for the deficit of high energy solar neutrinos. Unfortunately, these nonstandard models generally have difficulties accounting for other observed features on the sun.

In addition to solar model effects, it has also been suggested that our understanding of the relevant particle physics may be incomplete. Mikheyev and Smirnov [10] and Wolfenstein [11] (and legions of others [12]) have pointed out that matter oscillation effects could enhance neutrino oscillations in the sun and explain the deficit. A neutrino magnetic moment [13-14] and neutrino decays [15] have also been invoked, as have weakly interacting massive particles [16], and extra quarks in nuclei [17].

The plethora of theoretical explanations makes exceedingly clear the need for experimental results capable of discriminating among models. In addition, the key assumption that neutrinos are produced as a result of proton-proton fusion in the sun must be checked directly. So far only radiochemical experiments can provide the low background and low threshold required to study the p-p flux.

Gallium, with a threshold of 0.23 MeV, is so far the only feasible target material capable of detecting the intense flux of the low energy p-p neutrinos via the $\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$ reaction.[18-21] The current observed energy output at the sun's surface corresponds to a neutrino flux of 6×10^{10} $cm^{-2}sec^{-1}$ from the p-p reaction alone, which corresponds to a flux of 70 SNU in the gallium experiment. This conclusion is based largely on energetic grounds, and is insensitive to the details of solar model calculations. This is based on the standard solar model calculations of Bahcall and Ulrich [1], the total counting rate in gallium, including all reactions, is expected to be 132 SNU. Observation of significantly less than 70 SNU with gallium would be very difficult to explain without invoking new neutrino physics.

2. The Baksan Gallium Experiment

Two gallium experiments are currently beginning or about to begin operation: the 30 ton gallium chloride GALLEX detector to be constructed in the Gran Sasso laboratory [22], and the 60 ton gallium metal detector in the Baksan laboratory in the USSR [19].

The Soviet-American gallium-germanium neutrino experiment is situated in an underground laboratory specially built in the Baksan Valley of the Northern Caucasus, USSR. The laboratory is 60 m long, 10 m wide, and 12 m high. It is located 3.5 km from the entrance of a horizontal adit driven into the side of Mount Andyrchi, and has an overhead shielding of 4700 mwe.

a) Extraction Procedure

The metal procedure has been worked out independently and fully tested in the USSR [19] and the US [23], and has been proven to work satisfactorily with a full-scale prototype.

The gallium is contained in chemical reactors, each with internal volume 2 m^3 and lined with teflon. The reactors are provided with stirrers and heaters that maintain the temperature just above the gallium melting point. Each reactor holds about 7 tons of gallium.

At the beginning of each run, a known amount of nonradioactive germanium carrier is added to the gallium in the form of a solid Ga-Ge alloy. The reactor contents are stirred so as to thoroughly disperse the carrier throughout the Ga metal. After a suitable exposure interval (3-6 weeks), the Ge carrier and any ^{71}Ge atoms that have been produced by neutrino capture are chemically extracted from the gallium. Details of the chemical extraction procedure have been described in detail elsewhere [28]. Basically, a weak solution of HCl, H_2O, and H_2O_2 is added to the reactors, and stirred together with the gallium. The Ge atoms go into solution and are extracted along with the solution. The solution is then reduced and the germanium is extracted from into H_2O. The Ge [27] is then extracted into CCl_4 and then back-extracted into tritium-free H_2O. The Ge is then synthesized into GeH_4 and mixed with Xe and used to fill small proportional counters.

b) Counting

^{71}Ge decays, with an 11.4 day half life, by electron capture to the ground state of ^{71}Ga. The only way to register such a decay is to detect the low-energy Auger electrons and x-rays produced during electron shell relaxation in the resulting ^{71}Ga atom. These low-energy electrons are detected in a small-volume proportional counter similar to that used in the Cl-Ar experiment. If xenon is mixed in with the germane, then (with a 90%-10% mixture of Xe-GeH_4 and measured detection efficiencies) we observe 41% of the decays in the L peak at 1.2 keV and 41% in the K peak at 10.4 keV.

The standard solar model predicts a production rate of 1.2 atoms of ^{71}Ge per day in 30 tons of Ga. At the end of a 4 week exposure period, and folding in extraction and detection efficiencies, the mean number of detected ^{71}Ge atoms in each run is only 4.0.

The major source of background in the counters is local radioactivity. The counters are therefore made from materials especially selected to have a low radioactive content, and are housed in large passive shields. The counting is conducted deep underground (at a depth of 4700 meters water equivalent) where the muon flux is measured to be only 2.4 +/- 0.3 x 10^{-9} cm^{-2} sec^{-1}. The laboratory is lined with a 6 mm steel shell and 60 cm of low radioactivity concrete. To further reject and to characterize background events, 13 of 19 counting channels currently have an active NaI detector around the proportional counter that is used in coincidence/anticoincidence.

Background radioactivity primarily produces fast electrons in the counter. In contrast to the localized ionization produced by the Auger electrons from ^{71}Ge decay, these fast electrons give an extended ionization signal as they traverse the counter interior. Since the risetime of the induced pulse increases as the radial extent of the ionization distance, it is possible to use pulse shape discrimination to separate the ^{71}Ge decays from the background.

Good rejection of background events is obtained with a counting mixture of 10% GeH_4 and 90% Xe. This gas mixture gives a resolution of 18-21% at 5.9 keV, with a measured total counting efficiency in a 2 keV (FWHM) window around 10.4 keV of 35%. This efficiency includes geometrical effects inside the counter and excludes events whose risetime is outside a 95% acceptance window. The analysis now searches for those events with acceptable values of both pulse height and ADP (or, in the case of the full waveform analysis, for events that can be well fit to a waveform of the expected shape and amplitude), and that occur at times consistent with the 11 day ^{71}Ge decay (i.e., events that occur early in the run, before the counting rate has decreased to a constant background).

c) ^{71}Ge Background

The main source of ^{71}Ge in the reactors other than from solar neutrinos is from protons arising as secondary particles produced by *i)* external neutrons, *ii)* internal radioactivity, and *iii)* cosmic ray muons. These protons can initiate the reaction ^{71}Ga(p,n)^{71}Ge. Extensive work has gone into measurements and calculations of these background channels.[23-26] The sum of all of these backgrounds has been determined to produce less than 0.03 ^{71}Ge atoms/day.

Since these sources of ^{71}Ge background have been made small, the major difficulty for the experiment is the need to remove from the gallium the large quantities of long-lived ^{68}Ge (half life = 271 days) that were produced by cosmic rays while the gallium was on the surface. ^{68}Ge decays only by electron capture, so its decays cannot be differentiated from those of ^{71}Ge. The subsequent decay of ^{68}Ga (half life = 1.14 hours) is by positron emission in 90% of the cases. These ^{68}Ga decays can generally be identified by rise-time analysis of the counter pulse and by detection of a coincidence pulse in the surrounding NaI crystal.

Another type of background that arises only during counting can come from tritium in the counting gas. In order to eliminate this source of counter background, special methods for synthesizing $NaBH_4$ have been developed [26] using starting ingredients selected to have a low tritium content.

3. Present Experiment Status

The experiment began operation in April 1988 when filling of the reactors started, and the experiment now contains 30 tons of gallium in four reactors. Each reactor has undergone at least 20 extractions to remove the germanium isotopes that were produced by cosmic ray interactions while the Ga was on the surface.

The efficiency of extraction of germanium from the reactors is measured at several stages of the extraction procedure. The major uncertainty in these measurements is in the amount of Ge carrier added to the reactors, which is determined to an accuracy of +/- 5%. The overall extraction efficiency from the Ge added to the reactors to the synthesized GeH_4 is approximately 75%. The standard procedure is to conduct three extractions in series within a period of 5 days without adding additional carrier to the reactors.

The total background rate of selected counters filled with 90% Xe, 10% GeH_4 has been measured in the energy interval of 0.7-13.0 keV to be approximately 1.5 events per day. In the region of the Ge K-peak energy, the counter background is 1 event per month.

Counting of the germanium samples began during the extraction of the germanium isotopes produced by cosmic ray interactions. After the gallium had been stored underground for 3 months, the initial activity of the Ge in the 30 tons of Ga was 7700 events per day in the energy region of the Ge K-peak. For recent runs, the activity in the Ge K-peak (35% counting efficiency) is less than 0.2 counts day^{-1}.

Some residual radioactivity is still present,which produces events in the energy range of 1-15 keV. In recent extractions this activity does not appear to be decreasing at the same rate as in the earlier extractions. Measurements of the activity obtained in various isolated steps of the extraction procedure have been conducted, but the statistics available are low. Although the source of this activity has not yet been definitely identified, it clearly comes from either the reactor vessels or the gallium, not from contaminants in the reagents. There is a possibility that there has been some diffusion of long-lived ^{68}Ge from the original dirty gallium into the teflon liners. Also, ^{68}Ge may be bound up in the gallium in another chemical form that is not extracted using the current procedure, although extensive chemical studies suggest this possibility is unlikely.

4. Future Plans

Monthly extractions from the 30 tons of gallium will continue. At the same time, further tests to understand the source of the remaining background will be conducted, and the detector will be expanded to the full 60 tons of gallium. Additional counting channels are also being installed. At the background levels presently achieved, the full 60-ton detector should yield a statistical accuracy of better than 25% after one year of operation (assuming a production rate of 132 SNU).

A calibration of the detector is planned using a ^{51}Cr neutrino source. It is expected that an activity of 0.8 MCi will be obtained by irradiating about 200 g of enriched chromium (86% ^{50}Cr) in Soviet reactor SM-2 (thermal flux = 3.2×10^{15} neutrons cm^{-2} sec^{-1})[24, 27]. Approximately 400 decays from the ^{71}Ge atoms produced by this source are expected to be detected.

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