Results of the Gallium experiments

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ABSTRACT

The 2 Gallium experiments, GALLEX and SAGE, are now producing stable measurements of the solar neutrino fluxes of (resp.) $77.1 \pm 8.5$ (stat) $^{+4.4}_{-4.0}$ (syst), and $69 \pm 13$ SNU, confirming a deficit compared to the predictions of the Standard Solar Models (120 to 140 SNUs). The experiment with a calibrated intense neutrino source of GALLEX has convinced the scientific community of the validity and seriousness of the radiochemical results, since the measured source result is $0.97 \pm 0.11$ times the expected value. The sensitivity of the Gallium experiments to the pp neutrinos, and the general belief that the pp solar neutrino flux is well understood, has lead to the conclusion that a strong suppression of the $^7$Be neutrino flux is needed and is sufficient to explain all experimental data. A natural explanation for such a suppression is provided by the MSW mechanism of neutrino oscillations.

1 Introduction

For more than 3 decades, the Chlorine experiment [1] (with a threshold of 814 keV) has systematically measured less than the predictions of the Solar Models [2, 3], between 1/3 to 1/4 of what was expected, i.e, $2.55 \pm 0.25$ SNU (exp.) vs $8.0 \pm 1.0$ (Bahcall et al.) or $6.4 \pm 1.4$ SNU (Turck-Chièze et al.). It was interpreted either as deficiency of the radiochemical experiment or as a "deficit of Boron neutrinos", since those neutrinos from the inner core of the Sun are very much dependent on the central temperature. The Kamioka experiment [4] (with a threshold about 7.5 MeV) has confirmed from 1988 the existence of a deficit, but the difference in this water Cerenkov detector is only a factor of 2:

Kamioka/Bahcall = 0.49 $\pm$ 0.04 $\pm$ 0.06
Kamioka/Turck-Chieze = 0.70 $\pm$ 0.12

At that stage, the general feeling was that there was a solar neutrino problem, but strong doubts on the experimental results (Chlorine is a radiochemical experiment, Kamioka has a very large background) did not allow clear conclusions to be drawn. The 2 Gallium experiments, GALLEX [5, 6] and SAGE [7] are now bringing stable and convincing results, which shed some new insights on the solar neutrino problem.

2 The Gallium results

2.1 GALLEX

GALLEX is an international collaboration, mainly from European countries, with Israeli and American participation. The experiment, installed in the Laboratori Nazionali del Gran Sasso (about 3300 mwe), started data taking in 1991. The experiment consists of 30.3 tons of gallium in 100 tons of gallium chloride in HCl. The solar neutrinos interact with the $^{71}$Ga atoms, transform them into $^{71}$Ge. In the acid solution, germanium is volatile and the germanium atoms are swept out of the tank every 3 to 4 weeks, by a flow of nitrogen. For the SSM predictions of solar neutrinos, about one $^{71}$Ge atom is produced everyday; the mean life of $^{71}$Ge is 16.49 days, so one expects a dosen atoms every month to be trapped in the low radioactivity counters, which are counted in a low radioactivity environment for 6 months. Radioactive germanium undergo electron captures which are detected in the proportional counters filled with 1 cm$^3$ of a gas mixture with 30% Germane and 70% old Xenon. The L peak is at 1.17 keV and the K peak at 10.37 keV. The acquisition records the energy and the pulse shape, and signals are selected in an energy-risetime window to distinguish the germanium signals from the Compton backgrounds of less than 1 count per week. What is called the "GALLEX-I" phase corresponds to a total exposure of 324 days where the gallium was sitting in the first tank (called "B-tank") of the Gallium experiment in Gran Sasso. The gallium was then transferred to the second tank (called "A-tank"), which was designed with a thimble in order to allow the introduction of a source inside the tank. The total exposure time in the "GALLEX-II" phase was 649 days, after which the source experiment described in a following section was performed. The final results
for GALEX-I and GALEX-II are reported here. A
global maximum-likelihood fit to the data from the full
39 runs gives the result for GALEX-I+II [6] of 77.1
\pm 8.5^{+5.4}_{-5.4} SNU. The mean life of the decaying com-
ponent deduced from all L+K data is 15.1^{+2.8}_{-2.4} days,
in agreement with the known value for 71Ge of 16.49
days. The summary of the results for GALEX-I and
GALEX-II is given in figure 1, where the contributions
for known backgrounds has been estimated, measured and
substracted. The systematic errors include errors on
the background.

2.2 SAGE
SAGE is a Russian American collaboration, installed
under the Baksan mountains (4800 mwe). The target
consists of 57 tons of metallic gallium, distributed in 8
vessels. Gallium becomes liquid when it is heated above
303°K. The procedures for extraction of the germanium
atoms, counting and analysis are very similar to what
was described for GALEX.
The first results on 30 tons with only the K peak were
presented in 1990 and were low but since the first
publications, the results have improved and are close
to those of GALEX. The last published results from
SAGE [7] are

\begin{equation}
69 \pm 10(\text{stat.}) \pm 6(\text{syst.}).
\end{equation}

The results of both experiments are shown on
figure 1.

3 The chromium source experiments
Since the consequences of these results are crucial for
particle and astrophysics, it is very important to place
the trustworthiness of the experimental techniques be-
ond any reasonable doubt. The most straightforward
check is to expose these experiments to neutrino sources
with known activity levels and appropriate energy, un-
der conditions nearly identical to those used in solar
exposures. GALLEX has performed the first exper-
iment of this kind and its results are reported here with
details to be found in [8] and references therein.

3.1 Fabrication of the $^{51}$Cr source.
$^{51}$Cr is produced by neutron capture on $^{50}$Cr ; its
half-life is 27.706 \pm 0.007 days. $^{51}$Cr decays by electron
capture with a Q-value of 751 keV to the ground state
of $^{51}$V (90.14 \% branching ratio) and to the first excited
state (9.86 \pm 0.05 \%), which deexcites to the ground
state with emission of a 320 keV $\gamma$ ray. Aside from
the low intensity internal bremsstrahlung, the neut-
trino spectrum consists of four monoenergetic lines (746
keV (81 \%), 751 keV (9 \%), 426 keV (9 \%) and 431 keV
(1 \%).

Natural chromium consists of 4 stable isotopes.
The low natural abundance of $^{50}$Cr (4.35 \%) along with
the high cross-section of $^{52}$Cr makes it technically im-
possible to reach with natural chromium, the activity
level, \approx 50 PBq required for a neutrino source experi-
ment. The Kurchatov Institute in Moscow has provided
us with chromium, enriched in $^{51}$Cr (about 40 \%) and
depleted in $^{52}$Cr (about 1 \%) in the form of solid chro-
mium trioxide, CrO$_3$, which were delivered to Saclay
between 1992 and 1994. Severe specifications were
asked and met for possible impurities in the enriched
chromium, of the order of ppm for Na, La, Sc, Sb, Co,
Ag, Th, As, Tb and of ppb for Ga, Fe, Zn, Cd, Br, Te
and U.

Since CrO$_3$ is thermally unstable, it is unaccept-
able as a target for irradiation in a nuclear reactor. We
have transformed it into metallic chromium by electro-
lysis and broken the metal into irregular chips of \approx
1 mm$^3$ volume, outgassed under vacuum to remove the
large quantities of hydrogen that had been absorbed
during electrolysis, so that \approx 36 kg of product could be
placed in the nuclear reactor.

Siloé, located at the "Centre d'études nucléaires
de Grenoble" (France) and operated by CEA (Commiss-
sariat à l'énergie atomique), is a swimming pool reactor,
with 35 MW thermal power. The dedicated core for the
chromium irradiation was specially built and arranged
in a checker-board configuration for our purpose.

The chromium chips were placed in 12 special ir-
adiator containers that were constructed of zircalloy so
as to be as transparent to neutrinos as possible; two ir-
adiator containers were placed in each of the six crenels.
The chromium was exposed to an average perturbed
neutron flux of $5.2 \times 10^{13}$ n/(cm$^2$·s), with large vari-
ations around this mean value that depended on the
positions of the irradiator containers in the reactor. The
irradiation started at 10 am on May 27, 1994, and lasted
without any interruption to end-of-bombardment (EOB = t$_0$), June 20 at 6 am.

The irradiated material was unloaded in a hot
cell at Siloé. The chromium chips were then placed
in a sealed stainless-steel container and inserted into
a tungsten shield (8.5 cm wall thickness) for biological
protection. Very sensitive measurements showed that
the external dose at any position on the surface of the
tungsten shield was less than 7 $\mu$Sv/h [9], well below
the maximum 200 $\mu$Sv/h-level allowed by the safety au-
thorities. Gamma-ray spectroscopy outside the shield
showed activation of impurities in the chromium of Na,
Sc, Cu, As, Ag, and Sb at levels that are orders of magni-
dude lower than specified [9].

3.2 Measurement of the source activity.
The amount of irradiated chromium composing the
neutrino source within the tungsten shield was
35530 \pm 10 g. The activity of this source was determ-
ined by several fully independent methods, as described below.

a) Calorimetry. The calorimetric method has the advantage that, since it measures the activity of the total source, it does not depend on our ability to take representative samples. Immediately after insertion of the source into the tungsten shield, the total thermal power of the source was determined by placing the source-plus-shield configuration in a thermally shielded vacuum vessel and by measuring the rate of the ensuing temperature increase. By comparing the measured rate with that in similar measurements where known amounts of thermal power were supplied by a resistance heater to 35.5 kg of chromium metal, we deduce a source power of 362 ± 13 W at EOB. The mean energy release of $^{51}$Cr is known to be 36.51 ± 0.16 keV per decay, emitted in the form of 320 keV $\gamma$-rays (9.86% abundance), X-rays, and Auger electrons. Due to the very low rate of impurities in the chromium, the amount of energy deposited in the calorimeter by these contaminants is negligible. Thus we deduce that the source neutrino activity is 61.9 ± 3.0 PBq at EOB [10].

b) Neutronics and gamma-scanning. The knowledge of the neutron flux and of the relevant capture cross-section for producing $^{51}$Cr provides another method for evaluating the final activity of the source. The relative energy spectrum of the neutrons, as a function of the position in the median plane of the reactor, is found by numerically solving the neutron transport equation for the Siloé configuration described in [11]. An on-line neutron measurement in one crenel allows the overall normalization. The axial neutron-flux distribution is deduced from the activity measured in the radiator containers, as a function of the height above the median plane. The value of the source activity deduced from these neutron measurements is 64.4 ± 5.2 PBq at EOB [11].

Gamma-ray scanning of the 320 keV $\gamma$ ray, measured in half of the irradiators in the reactor pool, yields the total source activity in a more or less independent way: the result is 64.0 ± 5.2 PBq at EOB [11].

c) The ionisation chamber technique. 31 samples were taken in the hot cell to be measured after careful mixing of the contents of each irradiator. The activity of each very active sample (about 2 TBq/g) was measured via the 320 keV $\gamma$ ray, using an ionisation chamber which was calibrated with a standard $^{51}$Cr source [12]. As cross checks, some of these samples were totally dissolved, diluted, and aliquots taken, which were then assayed by gamma-ray spectroscopy, using Ge crystals calibrated with other absolute $^{51}$Cr standard sources. The results of these different absolute $\gamma$-ray measurements are consistent.

The variance of the 31 individual results is consistent with the assumption that the total of all these samples is representative of the full 35.53 kg of chromium. The average specific activity of the 31 metal samples is 1.71 ± 0.04 TBq/g [12] and, consequently, the total activity of the source is 61.3 ± 0.8 PBq at EOB.

d) Measurements with Germanium spectrometers. Samples of the Chromium were dissolved and measured in 3 different institutes of the collaboration (Karlsruhe, Heidelberg, Brookhaven) giving respectively values of 63.1 ± 0.9, 63.2 ± 0.9 and 63.1 ± 1.0 PBq.

e) Analysis of the Vanadium yield. The Brookhaven group has performed analysis of the $^{51}$V yield in the samples. They have tested the efficiencies of their extraction and irradiation processes and give a result of 62.3 ± 1.1 PBq.

f) Mean value of the $^{51}$Cr source activity. The first two categories are integral methods, the last ones depend on sampling. The agreement between the results of the independent methods discussed above allows us to take a weighted average of their values. The resulting mean activity of the $^{51}$Cr source at EOB in Siloé is $A_0(t_0) = 62.5 ± 0.4$ PBq, stated with one-σ error. A 'maximum error' approach yields $62.5 ± 1.9$ PBq taking the range of individual errors.

3.3 The Source experiment.

For the transport between Grenoble and Gran Sasso, the source inside its sealed tungsten shield was placed in a special certified container used for transport of radioactive material.

The total time from EOB to the introduction of the source into the reentrant tube in the GALLEX target tank at Gran Sasso was 3.69 days, equivalent to an 8.8% decrease of activity.

To avoid any heat transfer from the source to the gallium solution, which could change the kinetics of the germanium desorption, a copper thermal shield, cooled with tap water (601/h), was placed between the source and the wall of the reentrant tube. The chromium neutrino source was inserted in its final position, in the A-tank, on June 23, 1994 at 10:36 pm. It was removed on October 10 at 2 pm and returned to Grenoble.

The experimental conditions were kept exactly as in the solar runs, except that the collection of the $^{71}$Ge produced by the decaying $^{51}$Cr was optimized by doing shorter exposures. That is, the duration of each source exposure was selected so that about the same number of $^{71}$Ge atoms was desorbed in each run; in particular, the first desorption was done 3.35 days after the insertion of the source, while the last 5 exposures each lasted about 2 weeks. Data taking, counting procedures in these runs and the $^{71}$Ge data analysis were performed exactly as for our solar runs [6, 5].

However, the maximum likelihood fit to the time sequence of counter events of a given exposure has been modified to depend on three terms: $a_{CC}$, $a_0$ and $b$. $a_{CC}$ characterizes the production of $^{71}$Ge by the source.
(which decays with the $^{51}$Cr half-life) and is proportional to the activity $A_0$ at EOB, now treated as an unknown that is determined from the fit. $a_0$ characterizes the production of $^{71}$Ge by the Sun and by side reactions [5], and is treated as a constant input term; this production rate (0.76 ± 0.11 $^{71}$Ge atoms per day) is taken from solar exposures [6]. $b$ is the constant background during the counting. Only $a_0$, $c_r$, and $b$ are fitted.

The energy spectra of the events within the risetime windows give clear L and K-peaks with a decay time well fitted by the known lifetime of 16.49 days of $^{71}$Ge and a constant background.

Figure 2 presents the time dependence of these results during the course of the source experiment. The results for each run are plotted at the time that the exposure to the source neutrinos began. The horizontal lines show the duration of each exposure. The fitted half-life of the $^{51}$Cr obtained with the maximum likelihood method from these $^{71}$Ge data is 23.8 ± 3.2 days. The curve in figure 2 is the number of $^{71}$Ge atoms produced per day predicted from the measured $A_0$ value of the source, 62.5 PBq, assuming the known half-life of $^{51}$Cr plus the known 0.76 $^{71}$Ge atoms per day produced by solar neutrinos and side reactions.

From the global analysis of all 11 source exposures, we deduce a mean initial source strength $A_0 = 60.4 ± 6$ (statistical) ± 3.1 (systematic), i.e. 60.4 ± 6.7 after adding quadratically the statistical and systematic error. This value is to be compared with the directly measured $^{51}$Cr source strength, $A_0 = 62.5 ± 0.4$ PBq. The ratio of these values is

$$R = 0.97 ± 0.11,$$

where the quoted error includes the experimental errors in $^{71}$Ge counting and in the source activity determinations, but does not include errors in the neutrino-absorption cross-sections.

3.4 Conclusions on the GALLEX source experiment

The 40% deficit of the solar neutrino flux observed by GALLEX, as compared to the SSM prediction, cannot be attributed to experimental artefacts. This source experiment directly demonstrates the validity of the basic principles of the radiochemical methods used in our solar neutrino detector: on the order of ten radioactive atoms produced by neutrino capture can be removed from tons of target material, purified and counted quantitatively. No unknown systematic effects take place at a level ≥ 10%. Because of the similarity of the neutrino energy spectra from $^{51}$Cr and from the solar $^7$Be branch, this experimental result also means that GALLEX is able to detect $^7$Be neutrinos with close to full efficiency.

After the $^{51}$Cr source was removed from the GALLEX target, solar neutrino exposures recommenced on October 12, 1994. Another source experiment is planned in the autumn of 1995 to get statistical errors for the combined source experiment at the level of 4 years of GALLEX solar neutrinos.

3.5 SAGE source experiment

SAGE has also performed a source experiment. They have used 802 g of Chromium enriched at 92 to 93% in $^{50}$Cr. The irradiation was performed in a fast breeder reactor of 520 MW in Kazakhstan between September 4th 1994 and December 18, 1994. 13 tons of gallium have been exposed to the 505 ± 10 kCi source (with less than 2 Ci of impurities) from Dec. 26, 1994 for 4 months. The expectation is about 15 at/day on Dec 26, 1994 for a solar neutrino background of 0.3 at/day. Results should be available soon [7].

4 A $^7$Be solar neutrino problem

In order to explain all experiments, a suppression of the Boron neutrinos alone is not sufficient. In fact a strong suppression of the Beryllium or pp neutrinos is necessary. Since all solar models todate are very doubtful about suppression of pp neutrinos, what is left is a strong Beryllium neutrino suppression. A natural explanation is provided by the MSW mechanism of neutrino oscillations. This was discussed by S. Petcov [13] during this conference. In order to test this hypothesis and measure the eventual parameters involved, the future experiments that are on preparation will be very important. SuperKamiokande will start data taking in April 1996 and will provide negligible statistical errors [14]. Their main problem is the background. SNO will start in 1996 and should be able to measure neutral current interactions. Provided the neutron background is indeed as low as expected, observing the number of $\mu$ and/or $\tau$ neutrinos explaining the reduced solar neutrino flux would be an undeniable proof of neutrino oscillations! Borexino intends to measure the Beryllium neutrinos of 862 keV. The purpose of the next generation experiment, is to establish the existence or non existence of the MSW effect. The next generation after those experiments will be to measure precisely the parameters of the MSW effect, if it is there, but this is for another 4 seas conference [15, 16].

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References


[10] Saclay group, "Calorimetric measurements of the $^{51}$Cr source activity", GALLEX internal note GX-58, September 1995\textsuperscript{1}.


\textsuperscript{1}GALLEX internal notes are available on request by email at gallexcoord@vaxgs.lngs.infn.it.

\textsuperscript{2}Summary available on request by email at daniel@fr.cnrs.in2P3.fr
Figure 1: Results from GALLEX and SAGE since the start-up of the experiments.
Figure 2: Number of $^{71}$Ge atoms produced per day during the course of the source experiment (all 11 runs). The points for each run are plotted at the beginning of each exposure, with the horizontal lines showing the duration of the exposures. The predicted curve (dotted line), which decreases with the known half-life of $^{51}$Cr, is based on the relationship between the directly measured source strength and the 0.189 $^{71}$Ge production rate per day. The curve also includes the constant 0.76/day production rate due to solar neutrinos and side reactions (dashed line).