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Preliminary results from the second ^{51}Cr neutrino source experiment in GALLEX

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Abstract

The GALLEX collaboration performed a second ^{51}Cr neutrino source experiment during fall 1995. The full results from this second source experiment will not be available before the end of 1996. Meanwhile, we present a short description and preliminary results in this informal note. The (preliminary) value of the activity obtained from direct measurements has been found equal to (68.7 ± 0.7) PBq (with 1-sigma error). This value, which is about 10 % higher than the activity of the first source, was achieved by optimizing the irradiation conditions in the Siloé reactor and doing a longer irradiation of the enriched chromium. Preliminary results show that the ratio, R, of the radiochemically determined activity from ^{71}Ge counting $(57.1 \pm 6.8$ PBq) to the directly measured activity is (0.83 ± 0.10). The combined value of R for the two source experiments is (0.92 ± 0.08).

1 Introduction

The GALLEX detector was successfully tested in 1994 with a ^{51}Cr neutrino source [1, 2]. The result, quantified by the ratio, R, of the measured result in terms of ^{71}Ge produced by the neutrino source, divided by the directly determined source strength, was found to be 0.97 ± 0.11 [2]. From the beginning, it was planned to reirradiate the same material and to perform a second source experiment in the GALLEX detector. In this note, preliminary results of this second source experiment are given, along with some experimental details.

Most of the operations necessary to produce the second source experiment were very similar to the ones described in detail in [3] for the first source. We focus here on points which differ in the two operations. Although we used exactly the same enriched chromium (there was < 0.1 % burn-up during the first irradiation), the second irradiation was performed with a higher average neutron flux and for a longer time, leading to a higher activity.

The main difference between the two source experiments consists in the different duration times chosen for the exposures of the gallium target to the source. In the first one, the 11 exposure times were chosen to optimize the use of the source by producing about the same number of ^{71}Ge atoms per exposure. So, we used rather short exposures, ranging from 3 days to 2 weeks, and only one 3-week exposure at the end of the experiment. For the second source, the exposure times were chosen to resemble more closely the durations of the solar exposures : after two short exposures (3.3 and 4 days), we switched to two 3-week exposures (as in GALLEX I), followed by three 4-week exposures (as in GALLEX II). In total, 7 exposures were performed in this second source experiment.

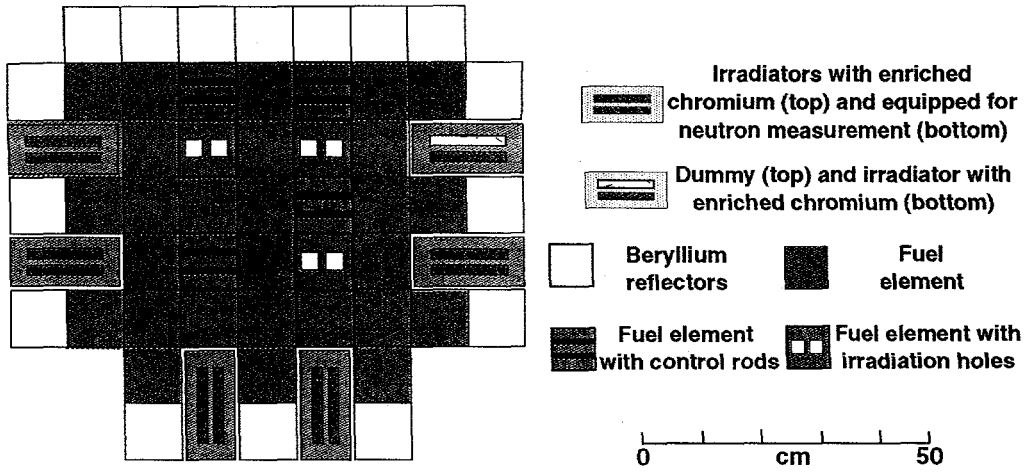

Figure 1: *Siloé core arrangement for the second irradiation.*

2 Production of the ^{51}Cr source

After the completion of the first source experiment (see [3] for complete details), the chromium source, still in its tungsten shield, was returned to Grenoble. Shortly after, it was unloaded in the hot cell and stored in plexiglass containers; prior to the second irradiation, it was transferred back into the same zircalloy irradiators used for the first irradiation.

Although the amount of chromium was the same, we chose to apportion the chromium chips among only 11 irradiators (instead of 12), just by filling each one more. Consequently, as seen in figure 1, the upper-right crenel has only one irradiator filled with chromium, the other being replaced by an aluminum mock-up (dummy) of the same size to minimize the perturbation on the neutron flux. This position was selected since it provided the least flux in the first irradiation. Taken together, the higher amount of chromium in each irradiator plus the one solid aluminum dummy increased the average neutron flux in the whole material.

Moreover, the beryllium reflectors were more efficient this time, due to a) a longer period of regeneration (irradiation with a low neutron flux to burn up the long-lived impurity, ^{10}B, which has a large, 3800-b neutron-capture cross section) prior to the dedicated period, and b) the fact that, on average, the reactor fuel elements had less burn-up. Altogether the average flux was 5.6×10^{13} n/cm^2.sec (7% more than for the first irradiation). Last but not least, based on the good operating experience we had had during the first irradiation, the safety/health physics personnel at Siloé gave us permission to irradiate for a few days more. Irradiation started on September 5, 1995 at 11 am and stopped on October 2, at 0h00 (defined as end-of-bombardment, EOB)

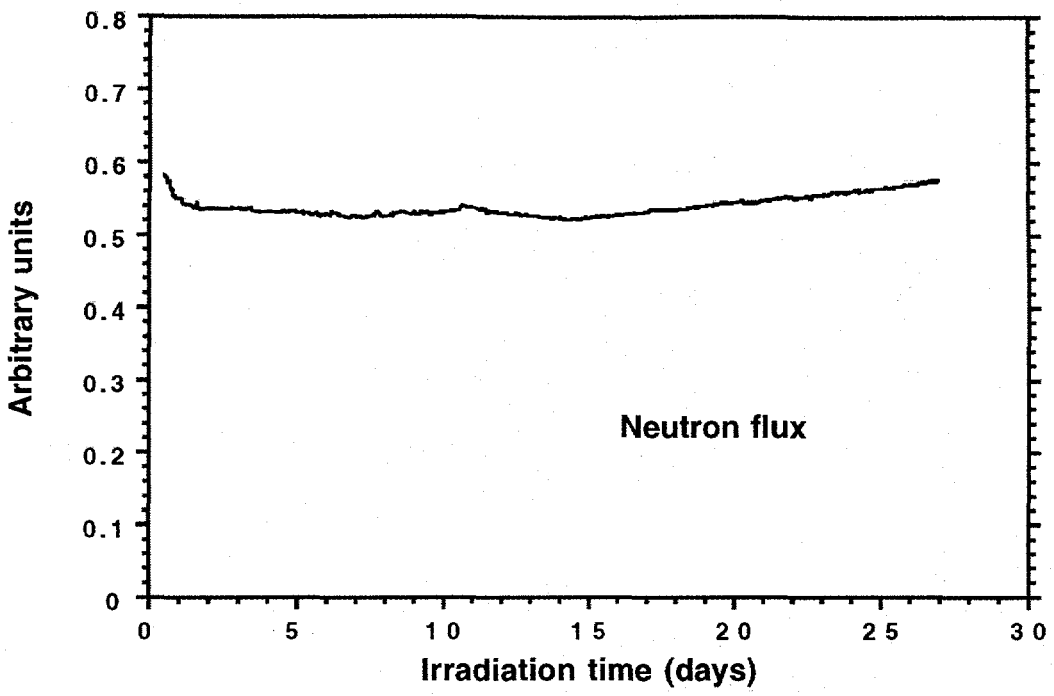

Figure 2: *Neutron flux as a function of time during the second irradiation.*

without any interruption. The evolution of the neutron flux during the irradiation is shown in figure 2 and is similar to the first irradiation [3].

The irradiation lasted 26.5 days instead of 23.8 days for the first source. Chromium unloading operations started after 6 h of cooling time.

3 Measurement of the activity

The total amount of irradiated chromium composing the second neutrino source is $35\,600 \pm 10$ g, 80 g more than for the first source. In the following, the quoted activity refers to the activity at EOB.

3.1 Sampling and activity measurements based on the 320 keV line

The full amount of chromium chips was unloaded from the irradiators and mixed in the hot cell, as described in [3]. The sampling procedure was modified to collect more samples than for the first source. As in the first experiment, 30 samples with an average weight of 0.56 g each were collected and put into individual lead containers, for activity measurements at Saclay by the ionisation chamber technique. In addition, we performed 3 sampling operations to collect one large representative sample of 41.4 g.

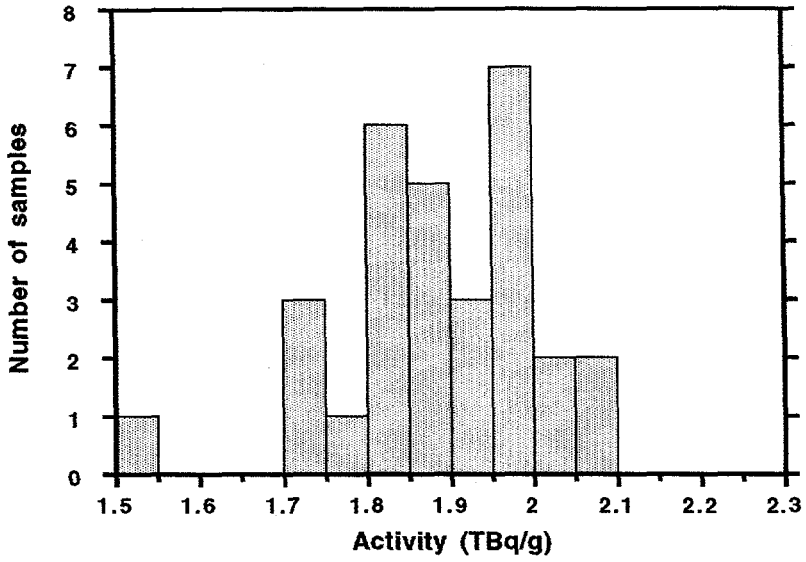

Figure 3: *Distribution of the activity of the 30 individual samples as measured by the ionisation chamber method.*

In Saclay, the activity of the 320 keV line from each small sample was measured in the ionisation chamber, which had been calibrated with a standard ^{51}Cr source. The individual results are displayed in figure 3. The dispersion of the distribution reflects true heterogeneities in the activities of the small samples. The precision of the method is ca. 1-2 %. The average specific activity of the samples is 1.895 TBq/g, and hence the total activity deduced is (67.5 ± 1.3) PBq.

At FzK, Karlsruhe, the large sample was split into 3 parts, each to be dissolved in 200 ml 3M H_2SO_4, and diluted to 1000 ml. The obtained sample had a concentration of 19.1914 mg Cr/ml. A dilution by a factor 10000 was followed by a chromium analysis (by ICP-AES, Inductively Coupled Plasma-Atomic Emission Spectroscopy) that showed (with a precision of 2 %) that the dissolution was complete. The large dilution factor allowed us to measure directly the 320 keV line with a Ge crystal at FzK and at Heidelberg. The measurement at FzK gave a value of (70.3 ± 1.5) PBq. At Heidelberg, part of the diluted solution from FzK was measured by γ-ray spectroscopy ; calibration was made with a standard ^{51}Cr source from PTB (German Office for Physical and Technical Standards and Measures). The result obtained was (68.3 ± 1.0) PBq.

3.2 Calorimetry

In the period between the two source experiments, the thermal insulation of the cryostat has been improved. New calibrations of the calorimeter with a calibrated

electric heat source have been performed prior to the measurements with the new source. The calorimetric measurement started in Siloé 60 h after the end of bombardment (6 h later than for the first source). For 16 hours, immediately before the shipment to Gran Sasso, we recorded the increase of temperature of the tungsten shield due to the heat generated by the ^{51}Cr when placed in the thermally insulated vessel. Combining these data with the calibrations done with electric heating, we deduce a total activity of (65.2 ± 6.0) PBq.

3.3 Vanadium content

After nearly complete decay of ^{51}Cr , analysis of its daughter ^{51}V was carried out in Karlsruhe by two methods (ICP-AES and AAS, Atomic Absorption Spectroscopy). The average result in terms of ^{51}Cr activity at EOB is (72.1 ± 3.0) PBq. (Vanadium coming from the first irradiation has been taken into account).

3.4 Activity from neutron measurement during irradiation

The knowledge of the flux of neutrons and the relevant cross sections to produce ^{51}Cr provides an independent method to evaluate 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 solving numerically the transport equation in Siloé with the set-up described in figure 1. The on-line direct neutron measurement by neutron flux monitors in one crenel gives the overall normalisation. The axial distribution is deduced from the profile measured in the first source experiment. From these inputs a total activity of (75.1 ± 6.0) PBq is derived.

3.5 Trace elements and ratio of activities

Impurities in the chromium are activated during the long irradiation period. Among them, there are several elements that are detectable at ppm levels via long-lived nuclides such as ^{110m}Ag and ^{124}Sb. Precise measurements have been performed outside the tungsten shield with Ge-crystals to detect energetic gamma rays that were emitted by the whole source. Results of these measurements [4] performed with the first source can be compared to the same measurements, performed at the same position with the second source, assuming that there were no changes in impurity concentrations between the first and second irradiations. Although these measurements were performed for safety purposes, we can compute the ratio of the activities for the impurities, corrected for the burn-up factor, to compare the activities of the two sources. Using this method, the second source is found to be $(10 \pm 2)\%$ more active than the first one. This relative measurement is not used for the computation of the mean value, but is in good agreement with it (see next subsection).

3.6 Mean value of the source activity

The mean values obtained by the different methods are recapitulated in table 1. Combining all these independent activity measurements, we deduce an initial activity of the source at the end of irradiation in Siloé of (68.7 ± 0.7) PBq. This value has to be considered preliminary since results from additional methods are not yet available and all of the planned checks have not yet been performed. As for the first source [3], a more conservative estimate of the error could be the "maximum error" on the mean, which takes into account the range of individual results and which yields $^{+6.4}_{-3.5}$ PBq. To fix this point, the different systematic errors on the different methods are presently being reanalyzed and the final error will be given in the final paper on the source results.

Method	Laboratory	Value (PBq)
Ionization chamber	Saclay	67.5 ± 1.3
Ge spectroscopy	Heidelberg	68.3 ± 1.0
Ge spectroscopy	Karlsruhe	70.3 ± 1.5
V analysis	Karlsruhe	72.1 ± 3.0
Calorimetry	Grenoble/Saclay	65.2 ± 6.0
Neutronics	Grenoble	75.1 ± 6.0
Weighted mean		68.7 ± 0.7

Table 1: *Summary of the different measurements of the source activity, quoted at EOB (preliminary values).*

From the end of irradiation in Siloé, the operations at Grenoble and the transport to Gran Sasso took 3.95 days before the source was introduced into the thimble of GALLEX, corresponding to a decrease of activity of 9.4 %.

4 Source experiment and results

A thermal shield, made of copper and cooled with tap water (60l/h) is placed between the source and the wall of the thimble in order to avoid any heat transfer to the gallium solution, which could change the kinetics of the desorption. It is equipped with thermocouples which record the decrease of heat emitted by the source during the whole experiment (figure 4).

The second source experiment started on October 5, 1995, at 22h47, when the ^{51}Cr neutrino source was inserted in its final position, in the middle of the A-tank (at a position 32 cm lower than the position of the first source). To optimize the number of ^{71}Ge atoms produced, the two first exposures were kept short, but all subsequent exposures were of 3 to 4 weeks duration. During the last exposure (S144), the usual procedure was modified in that the target solution was slowly mixed every day by closed-loop gas circulation, the same procedure used for mixing after introduction

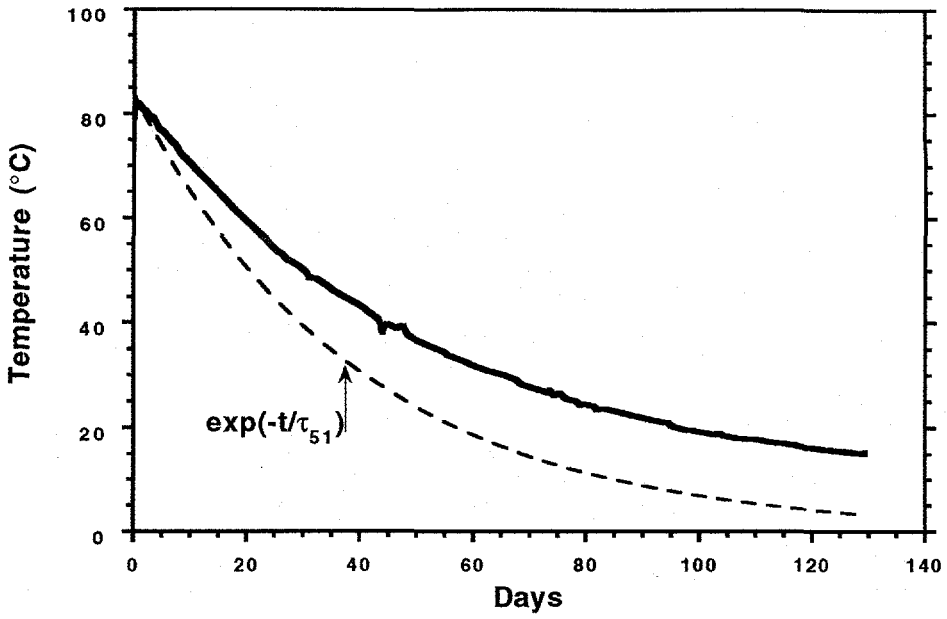

Figure 4: *Temperature of the tungsten shield during the second source experiment.*

of the Ge carrier. Since no blank runs were made between exposures, a correction has to be applied to take into account ^{71}Ge production during extraction as well as carry-over of ^{71}Ge atoms from one source exposure to the following one [5].

The parameters of the 7 extractions that were performed in this source experiment are given in table 2.

An unusually large radon signal was observed for exposure S142, reducing the effective counting time for ^{71}Ge to 72% (instead of 92% for typical runs); this effect has been taken into account in the analysis. The standard analysis is performed exactly as for the first source with two components: one that decays with the ^{51}Cr lifetime and represents production of ^{71}Ge by ^{51}Cr neutrinos, and a second, constant term that corresponds to the production of ^{71}Ge by the Sun and by side reactions. The latter term has been taken equal to (0.69 ± 0.11) ^{71}Ge atoms/day. The program fits the value of the initial activity of the source at EOB at Siloé, taking into account the appropriate elapsed time (see [1] for details). Since the normal counting period of 6 months has not yet been achieved for all of the runs, these results are still preliminary.

As seen in figure 5, a clear accumulation of events in the L and regions for fast risetimes shows the dominant ^{71}Ge signal above a very small background.

The results from table 1 of each individual exposure are displayed on figure 6. We note the large deviation of the third data point, run S140 (which is expected to contain about 30% of the data), from the expected curve. A global fit to all of the ^{71}Ge data gives a value for the source activity at EOB of $(57.1 \pm 6.2\,(\text{stat.}) \pm 2.8\,(\text{syst.}))$ PBq. The ratio, R, between this activity deduced

Run	Start of exposure	End of extraction	Days after EOB	Exp. length (days)	Yield (%) (a)	Counter type	Activity (PBq) (b)	^{71}Ge produced per day (c)
S138	Oct. 5 22.47	Oct. 9 7.00	3.9	3.3	95.6	SC	61±17	11.2±3.1
S139	Oct. 9 7.00	Oct. 13 7.00	7.3	4.0	92.7	HD2	66±19	11.1±3.2
S140	Oct. 13 7.00	Nov. 1 7.00	11.3	19.0	98.4	SC	49±9	7.6±1.4
S141	Nov. 1 7.00	Nov. 22 7.00	30.3	21.0	94.9	HD2	69±15	6.8±1.5
S142	Nov. 22 7.00	Dec. 20 7.00	51.3	28.0	99.4	HD2	54±21	3.5±1.3
S143	Dec. 20 7.00	Jan. 17 7.00	79.3	28.0	97.2	HD2	42±31	1.8±1.3
S144	Jan. 17 7.00	Feb. 14 7.00	107.3	28.0	97.3	SC	127±60	2.3±1.1

Table 2: *Characteristics and results of the exposures performed in the second source experiment.* [(a)] *The yield values are the corrected ones (see [6] for details).* [(b)] *The activity values are given at EOB.* [(c)] *Ge per day is stated at the beginning of each exposure period (statistical error only).*

from ^{71}Ge counting and the directly measured source activity, (68.7 ± 0.7) PBq, is equal to (0.83 ± 0.10).

The agreement between the predicted and the measured signal is less satisfactory than for the first source experiment, being 1.7σ from the first Cr result. Possible systematic effects are being considered, but so far we have no indications of any experimental effects that might lower the results.

We should also note that the value of the underlying neutrino cross section contains an excited state contribution. In discussing the results for exposure to the ^{51}Cr source [1], we used as a standard value of the cross-section of ^{51}Cr neutrinos the value stated in the review of Bahcall and Ulrich [8], $(59.2 \pm 6.0) \times 10^{-46}\,\mathrm{cm}^2$; this value includes estimated contributions of 5 % attributable to excitation of those excited states of ^{71}Ge that are energetically reachable. Unlike the very well determined ground state strength, these weak excited state cross-sections are estimated from (p,n) studies [9] that are necessarily not as firmly connected to the weak interaction mechanism. If we leave open the excited state contribution, the expectation for ^{51}Cr is then $R \geq 0.95$.

A reevaluation of the ^{71}Ge activity for the first source experiment has been recently made, mainly due to updated determinations of the germanium yields by mass spectrometry. The corresponding value of R is 1.00 ± 0.11 (instead of 0.97 ± 0.11 [2]). A combined analysis of the two source experiments has been performed, ask-

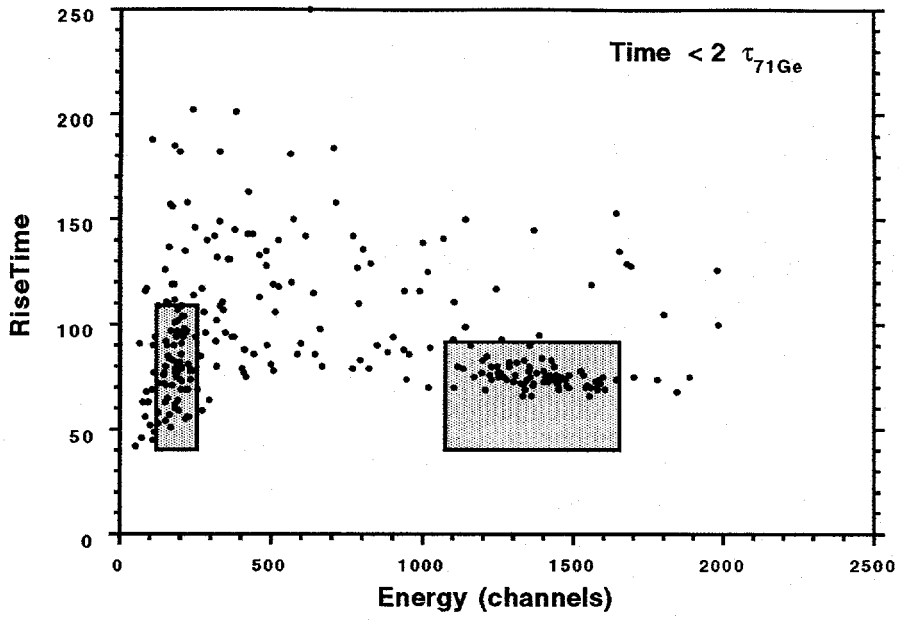

Figure 5: *Risetime vs energy for events in the first 33 days of counting.*

ing the program to fit directly a single number for the ratio R, using the value of the directly measured activity of each source as a normalization. This analysis gives $R = 0.92 \pm 0.08$ [1].

5 Conclusion

In the fall of 1995, GALLEX performed a second experiment with a reactor-activated, intense neutrino source. It was done by re-irradiating in the Siloé reactor the same 35.6 kg of enriched chromium used for the first source experiment. Optimized experimental conditions and a longer irradiation time brought the source to an activity of (68.7 ± 0.7) PBq as measured by various independent techniques, 10 % higher than that of the first source. Except for the two first exposures, the duration of the 5 following exposures was similar to the duration of solar exposures (3 to 4 weeks). The experiment started on October 5, 1995, when the source was introduced into the thimble in the gallium target solution and ended on February 13, 1996, at the removal of the source.

The results are still preliminary, since the counting is not yet completed for all runs. The ratio between the activity deduced from ^{71}Ge counting to the activity

[1] The alternative pulse shape analysis method [7] also used in Ref. [6] gives $R = 0.85 \pm 0.10$ for the second source and $R = 0.93 \pm 0.08$ for the two sources combined. These values are in good agreement with the values quoted above, obtained with the standard GALLEX analysis. We refer to Ref. [6] for a discussion on the two methods.

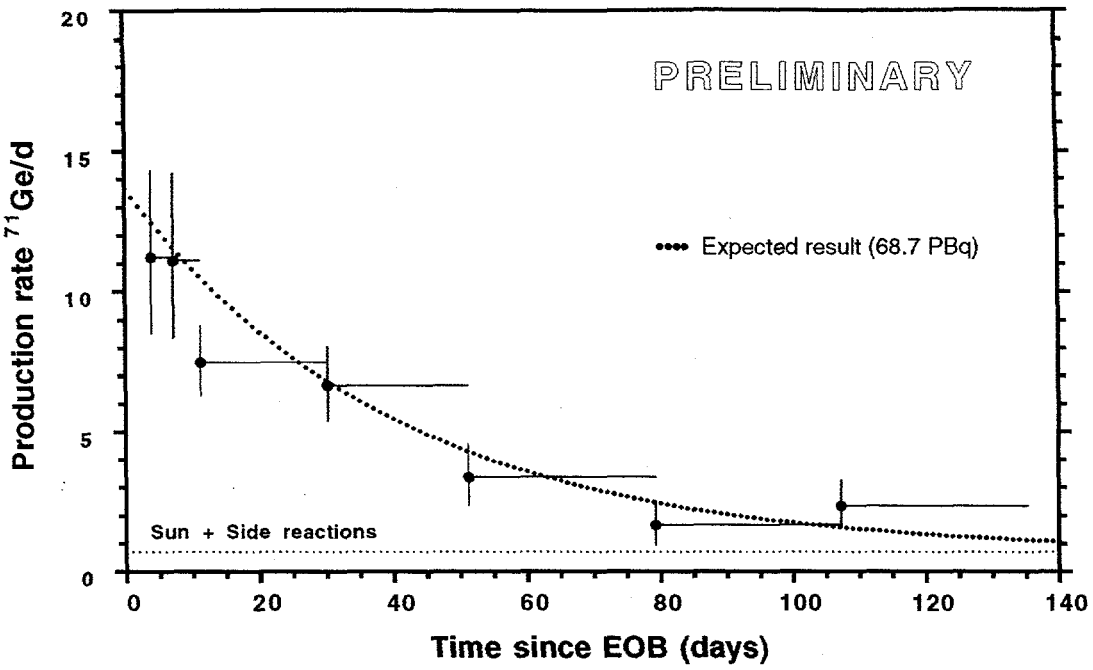

Figure 6: *Number of ^{71}Ge atoms produced per day in the second source experiment. Vertical bars are statistical errors; the horizontal bars do not represent errors, but are the lengths of each run. The dotted line corresponds to the expected rate for a source activity of 68.7 PBq; it is not a fit to the data points.*

measured directly is 0.83 ± 0.10. If we analyze the results of the two source experiments taken together, we obtain a value of the ratio 0.92 ± 0.08.

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