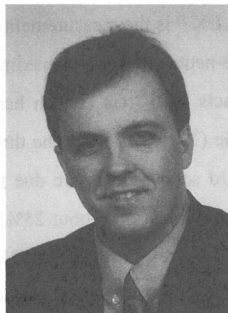


GALLEX RESULTS FROM THE FIRST 30 SOLAR NEUTRINO RUNS

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ABSTRACT

GALLEX, located in the Gran Sasso Underground Laboratory, has observed the Sun for about 2.5 years to determine the production rate of ^{71}Ge from ^{71}Ga induced by solar neutrinos. The target consists of 30.3 tons of gallium in form of 101 t galliumchloride-HCl solution. 30 solar runs give a combined result of $[79 \pm 10 \text{ (stat.)} \pm 6 \text{ (syst.)}] \text{ SNU}$ (1σ) whereas 19 blank runs yield a zero signal. The difference between our result and the predictions from solar model calculations (122 SNU - 132 SNU) could originate either in an inadequacy of the solar models to fully describe the details of the solar interior or in non-standard neutrino properties (neutrino mass).

1. INTRODUCTION

The radiochemical Chlorine Detector measures a production rate due to solar neutrinos of 2.32 ± 0.23 SNU ¹⁾ (1 Solar Neutrino Unit = 1 neutrino capture per second in 10^{36} target atoms). The difference between this result and the ≈ 8 SNU predicted by standard solar models (SSM) ^{2,3)} represents the so called 'solar neutrino problem', which has been confirmed by the Kamiokande water Cerenkov detector measuring only $[50 \pm 4$ (stat.) ± 6 (syst.)] % of the SSM expectation ⁴⁾. One feature of both detectors is that they measure mainly the high energy ^8B neutrino flux.

Contrary, the main goal of GALLEX ⁵⁾ is the measurement of neutrinos from the primary proton-proton fusion in the Sun. These pp-neutrinos have a maximum energy of 420 keV. In the basic GALLEX-reaction a solar ν_e interacts with ^{71}Ga (which has 39.6% abundance in the 30.3 t Ga target) and produces radioactive ^{71}Ge ($T_{1/2} = 11.43$ d). The threshold is 233 keV. About 55% of the production rate predicted by standard solar models are due to these ν_{pp} , the other 45% split into neutrinos from the ^7Be electron capture reaction (about 25%), neutrinos from the ^8B decay (about 10%), and neutrinos coming from the pep reaction and the CNO cycle.

The experimental procedure of GALLEX, the data analysis, results and a short discussion of implications of these results in the frame of the Chlorine and Kamiokande experiments will be given in the next paragraphs.

2. EXTRACTION AND SYNTHESIS

GALLEX is installed in the Gran Sasso Underground Laboratory where the target is shielded by about 1000 m of rock. The solution is contained in a 70 m³ tank. Tank A, which has a bigger purging system and a thimble to take up an artificial neutrino source, was used for solar runs A59-A87 (15 runs), earlier tank B was used for runs B29 through B50 (15 runs). A capture rate of 79 SNU (GALLEX result) leads to only about 10 atoms of ^{71}Ge present after 4 weeks of exposure. These few atoms have to be removed and detected.

2.1 Ge extraction

A single experiment in GALLEX (run) starts with the addition of 1 mg stable Ge-carrier which serves two purposes. The carrier allows the quantitative determination of the Ge-separation efficiency from the target and is later used as part of the counting gas. After 4 weeks exposure in tank A (3 weeks in tank B) the carrier and the few ^{71}Ge atoms have to be removed from the target. This is done by purging with about 2000 m³ of evaporated nitrogen using the fact that Ge is present

in the form of GeCl_4 which is volatile in the acid target solution. The germanium is then reabsorbed in large absorption columns filled with water and transferred by repetitive extraction and adsorption from some 10 l water at the beginning to 50 ml of tritium-free water in the end. These 50 ml are used to synthesize the gas Germane (GeH_4).

2.2 GeH_4 synthesis and counter filling

The GeCl_4 is reduced to GeH_4 by using sodium borohydride (NaBH_4). It is then cleaned by gas chromatography and the amount of gas is measured to determine the overall efficiency from step one, the addition of carrier, to the last step, the conversion to Germane. Finally the gas is filled into miniaturized proportional counters together with Xe to improve the counting performance. The GALLEX gas consists of 30 % GeH_4 and 70 % Xe at a pressure of 800 Torr.

The decay of ^{71}Ge is then observed in a proportional counter to indicate the ν_e -capture in ^{71}Ga . For a good determination of the low background each sample is counted for 180 d, which concludes one GALLEX run. For further details of the experimental procedure see ^{6,7)}

3. COUNTING

^{71}Ge decays with a half-life of 11.43 days by 100% electron capture. As mentioned the number of atoms present in the tank after exposure is only about 10 and the measured signal (including all efficiencies) consists of only about 5 decays detected. This low count rate requires different measures both in the counting facility and in the counter construction itself.

3.1 Counter construction and performance

In order to minimize the background of our proportional counters all materials were carefully selected in respect to their content in natural radioactive elements. The miniaturization of the counters also reduces the chance of events caused from natural radioactivity outside the counter ⁸⁾. The average countrate in the 30 solar runs in the L- and K-window (see below) which is due to background is 0.05 counts per day (cpd) and 0.02 cpd respectively. To shield the counter from outside disturbances (like electromagnetic radiation) which could also trigger events, it is imbedded in a lead shield surrounded with a copper housing also containing the preamplifier.

3.2 Counting facility

Up to 23 counters can be connected to different lines of a CAMAC data taking system. The whole system is installed in a Faraday cage and read out by a μ VAX linked with fiber optics. 8 lines feature an active anti-coincidence using a NaI-crystal (active position) which may serve as a diagnostic tool, the other 15 lines are shielded with an additional copper block (passive position). The most important data taken are *energy*, *NaI-veto* if available, *eventtime* and the *pulsshape* of the first 200 nanoseconds of an event.

The counting positions are installed in a tank (glove-box system including an air sluice) which keeps fresh air with its radon content outside also during counter connection and calibration. The radon content in the tank is being monitored. It is found to be on a low and constant level ^{6,7}.

4. DATA ANALYSIS

The raw result of 180 days of counting of a sample are typically a few hundred events with their mentioned characterizing datasets. Cuts have to be performed to reduce the background to the required level.

4.1 Cuts

Cut in NaI

The decay of ^{71}Ge is not accompanied by any gamma-rays, therefore any event which has a signal in the NaI can be discarded. The total number of events in 13 solar runs counted on the active position which is rejected by this cut amounts to 47% of all events before any cut.

Cut in energy

The ^{71}Ge decay results in two peaks in the proportional counter, the L-peak at 1.17 keV and the K-peak at 10.37 keV. The energy scale and the energy resolution are calibrated every 8 weeks with an external cerium-source giving 3 peaks at 1.03, 5.09 and 9.75 keV. The efficiency to count ^{71}Ge is determined through measurements of high statistic ^{71}Ge -samples away from Gran Sasso (to avoid any contamination risk) with the same type of counter as used in solar runs. These ^{71}Ge spectra are compared with the respective cerium spectra. This comparison yields energy efficiencies of typically 31% for the L-peak and 37% for the K-peak including dead volume effects in the counter.

Cut in pulsshape

Unlike extended events like e.g. Compton scattering events which ionize along a track in the counter, ^{71}Ge emits only low energy Auger electrons and X-rays leading to point like events. This leads to different pulsshapes. Background events have slowly rising pulses (the electrons arrive at different times at the anode wire), whereas ^{71}Ge events have fast rising pulse. The cut efficiency is calibrated like the energy cut efficiency and amounts to 97.7% in the L-region and 95% in the K-region.

Radon cut

^{222}Rn ($T_{1/2} = 3.825$ d) and its daughters have significant fingerprints as they decay in the counter because the three α -decays in the chain have very high probabilities to produce high energetic events (overflows). Therefore a general cut is performed which declares the 15 minutes *before* and the three hours *after* an overflow as deadtime. Another cut is based on the ^{214}Bi - ^{214}Po ($T_{1/2} = 164$ μs) decay which gives two events in a device recording 1 ms after each event. As the ^{214}Po decays to the quasi stable ^{210}Pb the three hours *before* a BiPo event are declared as deadtime. The cut efficiency measured with a radon-spiked counter is $(91 \pm 5)\%$.

After these cuts one is left with a time sequence of events (including ^{71}Ge and the remaining background) and ontime intervals for each single run. These time sequences have to be analysed to obtain the number of ^{71}Ge decays.

4.2 Analysis of the time sequences

The time sequences of all the runs are analysed with the maximum likelihood method ^{9,10}. The free parameters of the likelihood function are a ^{71}Ge production rate common to all runs and two background rates per run (for L- and K-window). Another parameter which enters as a fixed input in the function is the ^{68}Ge ($T_{1/2} = 271$ d) content for solar runs B29-B50. This ^{68}Ge content in the first 15 runs was a remaining part of cosmogenic produced ^{68}Ge in the solution ^{6,7}. For the runs in the A-tank A59-A87 there is no longer any contribution of ^{68}Ge .

5. RESULTS

The combined result for all 30 solar neutrino runs is $[79 \pm 10$ (stat.) ± 6 (syst.)] SNU (1σ). This result includes the subtractions due to non solar contributions and corrections for inefficiencies in the Rn-cut. Figure 1 shows the results for single runs and the combined analyses.

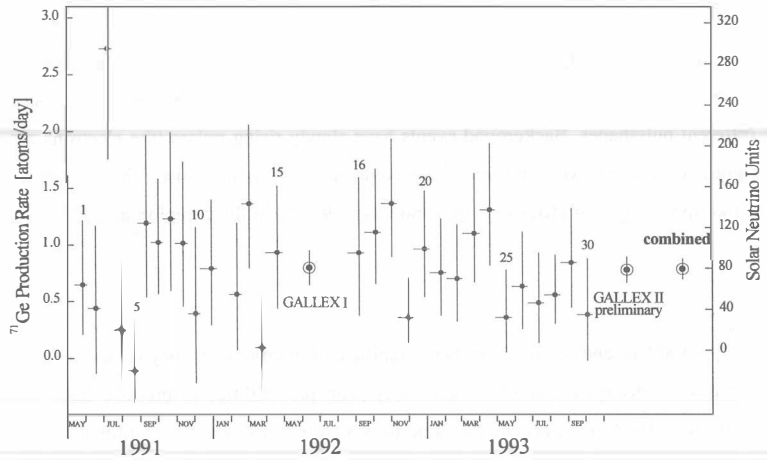


Fig. 1: Results for the 15 solar runs of GALLEX I and the first 15 runs of GALLEX II together with the combined results (1σ -error bars). The left-hand-scale shows the ^{71}Ge production rate, the right-hand-scale the results after subtraction of side-contributions.

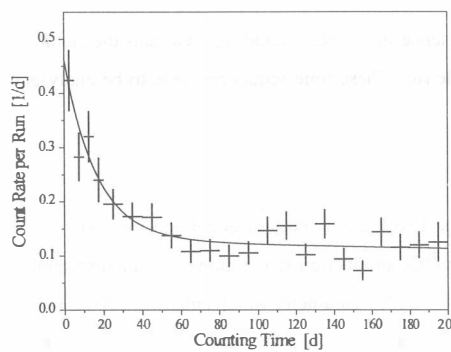


Fig. 2: Time distribution for 30 solar runs (see text)

Figure 2 shows the time distribution of the 30 solar runs. The solid curve is the maximum likelihood fit obtained with the fixed half-life for ^{71}Ge . A χ^2 -test gives a value of 17.8 for 20 degrees of freedom which corresponds to a Confidence Level of 60%. A maximum likelihood fit which leaves the half-life for the decaying component as a free parameter yields 11.8 ± 2.1 d in good agreement with the ^{71}Ge half-life of 11.43 d. Another

illustration for the presence of ^{71}Ge in the samples is shown in figure 3, where the energy spectrums of all fast events (according to their risetime) are plotted. The open bars represent events occurring within the first two meanlives of ^{71}Ge (33 days) whereas the closed bars show the events occurring during the last two meanlives of ^{71}Ge for the 30 solar runs. The two peaks at around 1 keV and 10 keV in the first two meanlives agree with the ^{71}Ge spectrum and have disappeared in the last two meanlives of counting.

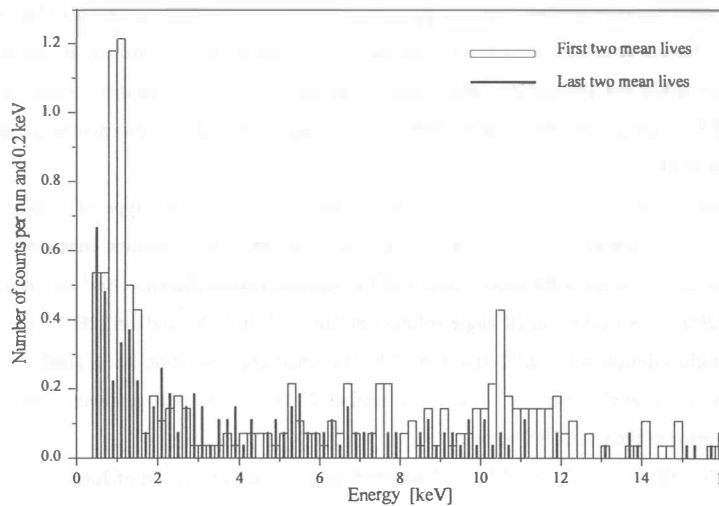


Fig. 2: Energy spectra of fast events in the first two meanlives (open bars) and the last two meanlives (closed bars)(see text).

Apart from the solar runs 19 blank runs have been performed. The characteristic of a blank run is its near-zero exposure time (24 hours exposure due to extraction), all other experimental steps are the same as in solar runs. The maximum likelihood treatment gave a result of (-1 ± 10) SNU, consistent with zero. This means that any effects or procedures that do not correlate with exposure time do not add anything to the solar signal.

6. DISCUSSION AND FUTURE

The observation of the Sun for about 2.5 years yielded a combined result for 30 solar runs of $[79 \pm 12]$ SNU (1σ). The latest result of the Russian-American Gallium Experiment SAGE ($[73 \pm 18]$ SNU)¹¹⁾ is now in good agreement. The GALLEX result resembles the prediction of a minimal solar model which just accounts for the solar luminosity. This prediction is 78 - 80 SNU, mainly from pp- and pep neutrinos (see e.g. Ref. ¹²⁾). This is appreciably less than the 122-132 SNU predicted in the Standard Solar Model, because of additional contributions from ^7Be and ^8B neutrinos in the latter. It is an open question whether the reduced flux of the higher energy neutrinos as measured in the Homestake and Kamiokande experiments is reduced since the SSM does not adequately describe all details of the state of the solar interior or because the electron neutrinos have mass and therefore undergo flavour transitions on their way to the detector. Since the GALLEX

signal can accommodate the full expected pp-neutrino induced production as enforced by the solar luminosity, there is no need to interpret the shortage as a consequence of neutrino mass. However, if one also considers the Homestake- and Kamiokande results, all data together cannot easily be conciliated by changes in the solar models and a solution related to new neutrino properties becomes more likely.

One such scenario which would reconcile all experimental results is a type of mixing among mass states, the MSW-effect ¹³⁾. If neutrinos do have a restmass these matter enhanced flavour-oscillations leave two areas for combinations of the squared mass-difference Δm^2 and the mixing angle $\sin^2(2\Theta)$, the so called small angle solution at $\Delta m^2 \approx 7 \times 10^{-6} \text{ eV}^2$ and $\sin^2(2\Theta) \approx 5 \times 10^{-3}$, and the large angle solution with $\sin^2(2\Theta)$ at 0.6 - 0.8. The small angle solution has a good χ^2 of 0.25, whereas the large angle solution has a χ^2 of around 7. This value will get even worse with a decreasing error of the GALLEX result.

GALLEX will continue the GALLEX II series of measurements until end of June 1994. Then an overall test of the whole experiment will be performed using a high intensity ⁵¹Cr-source ¹⁴⁾. After that the observation of the Sun will resume to reduce the statistical error to about 8% ¹⁵⁾.

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