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Review

Experimental and analysis methods in radiochemical experiments*

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Abstract. Radiochemical experiments made the history of neutrino physics by achieving the first observation of solar neutrinos (Cl experiment) and the first detection of the fundamental *pp* solar neutrinos component (Ga experiments). They measured along decades the integral ν_e charged current interaction rate in the exposed target. The basic operation principle is the chemical separation of the few atoms of the new chemical species produced by the neutrino interactions from the rest of the target, and their individual counting in a low-background counter. The smallness of the expected interaction rate (1 event per day in a ~ 100 ton target) poses severe experimental challenges on the chemical and on the counting procedures. The main aspects related to the analysis techniques employed in solar neutrino experiments are reviewed and described, with a special focus given to the event selection and the statistical data treatment.

1 Generalities on radiochemical experiments

Radiochemical experiments are a brilliant method to detect low energy (sub-MeV) neutrinos. The incoming ν is absorbed via the inverse beta decay reaction $\nu_e(N, N')e^-$ by a target nucleus N, generating a new isotope N'. The choice of the target nucleus is driven by the following requirements: i) The ν_e-generated atom must have different chemical behavior from the target atoms and molecules, to be extractable by specific physico-chemical procedures; ii) N' has a proper lifetime to integrate the neutrino flux over a convenient exposure time and to observe its decay back to N through a detectable characteristic signal.

Radiochemical experiments measure the ν_e capture rate $R^{\odot}_{\nu_e}$ at Earth, over an exposure time; they cannot directly measure the neutrino flux, arrival direction, time and energy distribution. Given the typical target masses they are ultra-low statistics experiments. In the '60s and '70s, when the radiochemical technique was developed, it was the only possible to detect sub-MeV solar ν_e.

The ν_e integral flux ($\sum_i \Phi_i$) can be derived from the interaction rate by the following relation:

$$R^{\odot}_{\nu_e} = N_{\text{target}} \cdot \sum_i \int \sigma(E) \cdot \frac{\mathrm{d}\Phi_i(E)}{\mathrm{d}E} P_{ee}(E)\mathrm{d}E \qquad (1)$$

once the ν capture cross section σ is known. $P_{ee}(E)$ is the probability for the neutrino to reach the detector as a ν_e. Being $\sigma \sim 10^{-46}\,\text{cm}^2$ and $\Phi_i \sim 6 \cdot 10^{10}\,\text{cm}^{-2}\text{s}^{-1}$, the natural unit to measure the solar neutrino capture rate is the SNU (Solar Neutrino Unit) $= 1\,\nu$ event/second each 10^{36} target atoms. It immediately follows that to have $O(1$ ν interaction per day), 10^{30} target nuclei $\sim O(100\,\text{tons})$, are needed.

The solar neutrino capture rate $R^{\odot}_{\nu_e}$ can be also expressed as

$$R^{\odot}_{\nu_e} = \frac{N_c \lambda}{\epsilon_e \epsilon_c (1 - e^{\lambda t_{\exp}})} - p_{ns}, \qquad (2)$$

$t_{\exp}$ is the target exposure time for a given observation, p_{ns} is the known rate of non solar production of N' in the detector (in the following referred to as side reactions), and λ the lifetime of N'. The growth curve of N' in the target saturates at the fraction $S = (1 - e^{\lambda t_{\exp}})$. Equation (2) describes the operation of a radiochemical detector, in the assumption of 100% live counting time when looking for the decay of N' back to N. $R^{\odot}_{\nu_e}$ can be derived once the N' number of neutrino-generated isotopes are counted (N_c), taking into account the extraction and counting efficiencies (ϵ_e, ϵ_c respectively). In sect. 2.2 the method how to take into account the counting dead time is illustrated. The first radiochemical measurement of $R^{\odot}_{\nu_e}$ was performed by Ray Davis on a chlorine target, and was first presented and published at the Neutrino Balaton conference in 1968 [1]. It was 24 years after the Pontecorvo

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idea to exploit the $\nu_e(N, N')e^-$ reaction [2] and 4 years after the publication of the first solar model [3]. Since then the chlorine and later from the beginning of the '90s, the two gallium experiments have continuously surveyed $R^{\odot}_{\nu_e}$. Until the first SNO result, in year 2002, they significantly contributed both to determine $(\Delta m^2, \theta_{12})$ and for solar astrophysics. In particular the gallium results, confirming the lack of low-energy $\nu_e^{\odot}$, indicated in the '90s that the solution of the so-called "solar neutrino puzzle" should be sought in the neutrino sector rather than in the Sun astrophysics or in solar models. In fact the flux of the *pp* neutrino is largely independent from the solar models and is strictly constrained by the solar luminosity. Until the very recent Borexino results [4] only Gallium experiments probed along a couple of decades the *pp* neutrinos.

2 Chlorine experiment

The chlorine experiment, located at the Homestake Mine in South Dakota at a depth of 4200 mwe, collected data between 1964 and 1994 but only the period 1970-1994, for a total of 108 $R^{\odot}_{\nu_e}$ independent measurements was included in the final analysis. The target of 615 tons of C_2Cl_4 (tetrachloroethylene), captured the neutrinos via and the inverse beta decay reaction $\nu_e(^{37}\text{Cl}, ^{37}\text{Ar})e^-$; the typical exposure time was 60 days, as the ^{37}Ar mean-life is 50.5 days. The expected unoscillated solar ν_e signal is 8.46 ± 0.88 SNU (6.86 ± 0.70 SNU) [5] for a high (low) metallicity Sun composition: including oscillations [6] the expected signal is 3.1 ± 0.3 SNU (2.53 ± 0.23 SNU), divided in 71.2% ^{8}B, 20.1% ^{7}Be, 4.6% *pep* + *hep*, 4% CNO. The experiment was checked for *hot chemistry* effects artificially spiking the detector with ^{37}Ar, but was never irradiated with a neutrino source. The final result is $R^{\odot}_{\nu_e} = 2.56 \pm 0.16 \pm 0.16$ SNU [7] or, combining the statistic and systematic errors, $R^{\odot}_{\nu_e} = 2.56 \pm 0.23$ SNU. The chlorine experiment was the first to raise the question of "missing neutrinos" from the Sun, and to confirm the mechanism of energy production by nuclear fusion in the stars. Moreover it studied the time behavior of the solar neutrino flux over a time period of a solar cycle. After many speculations in the '90s about correlation of the neutrino signal with the sunspot number, no evidence of significant correlation of the neutrino flux with solar cycle has been found [8]. Finally the chlorine experiment proved the feasibility of the radiochemical technique and opened the road to gallium experiments. Ray Davis, the scientist that conceived, designed and realized the experiment, was awarded in 2002 with the Nobel Prize in Physics for his *pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos*.

2.1 ^{37}Ar counting and event selection

The number of ^{37}Ar atoms extracted from the detector is determined by observing their decay in a miniature gas-filled proportional counter (MPC) of volume $\sim 0.5\,\text{cm}^2$. The Ar is extracted from the tetrachloroethylene target by He stripping. The argon sample extracted from the tank together with enough additional air argon to fill the counter to the required pressure of 1.1–1.2 atm is used to fill one MPC; the final mixture is about 93% argon and 7% low-tritium content methane. The main ^{37}Ar decay mode ($\tau = 50.5$ days) is the K orbital electron capture: 2.8 keV of energy are released in the MPC in form of Auger electrons. The MPC are operated in a large NaI detector, which in turn is surrounded by a thick passive shield: the shielding close to the MPC consists of 10 cm of purified mercury. All the events above a threshold of about 0.3 keV are recorded along the counting time of about 350 days from ^{37}Ar extraction time. ^{37}Ar decays in the MPC are then selected from background events on the basis of their energy and rise-time characteristics; for rise-time the adopted parameter is the Amplitude of the (analogically) Differentiated Pulse (ADP). Cutting on the ADP allows to enhance the ^{37}Ar on the background events (mostly Compton electron from γ scattering and β's), as Auger electrons produce fast pulses, corresponding to high ADP values, while βs generate slow pulses hence leading to low ADP values. Normalizing the ADP parameter to 1, the threshold for ^{37}Ar selection is 0.85 [7]. The most serious background source that can mimic the ^{37}Ar signature, both in energy and ADP, are the recoil nuclei from α decay: hence the MPC filling gas must be as low as possible in ^{222}Rn content.

2.2 Data analysis

The event selection process produces a time series of events that all fit the criteria for ^{37}Ar decay. Using this time series, a fit is made to a decaying exponential with an half-life fixed at 35 days (the of ^{37}Ar signal) plus a decaying background whose half-life can be varied. The analysis of background events (those happening after 175 days from the extraction date or low ADP events) from cumulative statistics gave a background half-life τ in the range 2–3 years. In both the cumulative time-rate plot and in individual counters the half-life observed is consistent with an half-life constant of $\tau_b = 2.7\,\text{yr}$. The results of the fit are two parameters, a production rate p of ^{37}Ar, and an initial background rate b of false events. Assuming p to be constant in the Chlorine target during the exposure and a decaying background rate in the counter with $\tau_b = 2.7\,\text{yr}$, then the probability for producing the observed time series of events is given by the following expression:

$$\mathcal{P}(t_1 \ldots t_n \mid p, b) \propto e^{-(N_b+N_c)} \prod_{i=1}^{n} \left(b e^{-\lambda_b t_i} + p \epsilon_e \epsilon_c S e^{-\lambda t_i} \right), \tag{3}$$

that is $\mathcal{L}$, the likelihood function. In the expression of $\mathcal{L}$, n and t_i are the total number and the occurrence times of the ^{37}Ar candidate events, respectively; λ and λ_b are the ^{37}Ar and the background decay constants, respectively, S is the ^{37}Ar saturation factor.

To introduce in the $\mathcal{L}$ expression the counting dead time intervals $\Delta = \sum_{k=1}^{m} (e^{-\lambda t_b k} - e^{-\lambda t_e k})$ is defined, where t_{bk}, t_{ek} are the beginning and ending time of kth counting interval, m is the total number of counting intervals, $N_b = \frac{b}{\lambda_k}\sum_{k=1}^{m}(e^{-\lambda_b t_{bk}} - e^{-\lambda_b t_{bk}})$ is the effective number of observed background events, and $N_c = p\epsilon_e\epsilon_c S\Delta/\lambda$ is the observed number of ^{37}Ar decays. The method of the maximum likelihood has been developed by B. Cleveland [9] in 1983; since then it has been adopted and is still in use in the data analysis of low statistics experiments, where a background and a signal components are both present, as in the gallium or in double beta decay experiments.

Fig. 1. One miniaturized proportional counters (MPC) handcrafted for Gallex/GNO [21].

3 Gallium experiments

3.1 Experimental details

From 1990 to 2005 two gallium experiments, GALLEX (GALlium EXperiment) and SAGE (Soviet American Gallium Experiment) continuously measured $R^{\odot}_{\nu_e}$ above 233 keV via the reaction $\nu_e(^{71}\mathrm{Ga}, ^{71}\mathrm{Ge})e^-$ originally proposed by Kuzmin in 1966. SAGE [10,11], located at the Baksan Neutrino Observatory in the Caucasus (4600 mwe overburden, leading to $\sim 0.1\,\mu$ /[h m^2]), is a Russia-USA collaboration and is still in operation. GALLEX [12] was a Germany-Italy-French-USA-Israel collaboration operating at LNGS-Italy (3500 mwe overburden, corresponding to $\sim 1.0\,\mu$ /[h m^2]). Since 1998 it was continued by the Italian and German groups of the original collaboration with the name GNO (Gallium Neutrino Observatory); the aim of the collaboration was to operate the experiment on a long time scale as a low energy neutrino observatory. GNO [13] took over the GALLEX apparatus, completely renewed the electronics, improved the ^{71}Ge counters calibration and the data analysis (details in sect. 3.2) and stopped the data taking in spring 2003 for important civil works at the hosting underground labs, and because of other non scientific reasons. The target is 49 tons (57 at the beginning of the experiment) of metallic gallium for SAGE, corresponding to ~ 20 t of ^{71}Ga, and was 103 tons of $GaCl_3 \cdot HCl$ in H_2O for GALLEX/GNO, corresponding to 30 tons of $^{\mathrm{nat}}$Ga or ~ 12 ton of ^{71}Ga[1].

Convolving the solar neutrino fluxes from [5] and the $^{71}\mathrm{Ga}(\nu_e, e^-)^{71}\mathrm{Ge}$ cross section that assumes a 5% contribution of the first two ^{71}Ge excited states in the ^{71}Ge to ^{71}Ge transition, the expected solar unoscillated Ga $R^{\odot}_{\nu_e}$ is 132 ± 18 SNU. If the contribution of the first two excited states is assumed to be zero, the expected unoscillated $R^{\odot}_{\nu_e}$ is $127^{+8.1}_{-8.2}$ SNU ($120.5^{+6.9}_{-7.1}$) for a high- (low-) metallicity Sun composition: including oscillations the expected signal is $66.31^{+2.9}_{-2.5}$ SNU ($63.16^{+2.6}_{-2.4}$ SNU) divided in 61.5% *pp* + *pep*, 28.2% ^{7}Be, 7% ^{8}B, 3.2% CNO (65.4% *pp* + *pep*, 26.6% ^{7}Be, 5.8% ^{8}B, 2.2% CNO) [14].

A new evaluation of $^{71}\mathrm{Ga}(\nu_e, e^-)^{71}\mathrm{Ge}$ cross section deduced from new $^{71}\mathrm{Ga}(^3\mathrm{He}, \mathrm{t})^{71}\mathrm{Ge}$ charge exchange experimental data recently appeared: the total unoscillated Ga $R^{\odot}_{\nu_e}$ of $122.4 \pm 3.4(\mathrm{stat}) \pm 1.1(\mathrm{syst})$ SNU for the full solar spectrum is expected [15].

[1] The isotopic abundance of ^{71}Ga is 39.9%.

The standard exposure time for solar runs was 3-4 weeks. In addition to solar runs, one-day-exposure blank runs were also frequently performed in order to verify the absence of any artifact or systematics related to the target. The absence of spurious effects or unknown background is confirmed by the small excess of ^{71}Ge counts in the blanks, consistent with the neutrino-induced production rate during the short exposure and the carry-over of the previous solar run: GALLEX/GNO and SAGE collected a total number of 123 and 168 useful solar runs, respectively. Beside several different experimental details, the main difference between the two experiments is the procedure to extract the ^{71}Ge from the target that translates into different *tank-to-counter* yield: 80–90% and (94.6 ± 0.3)% for SAGE and GALLEX/GNO respectively[2]. Both experiments were irradiated with artificial ^{51}Cr neutrino sources [16–18], and SAGE also with a ^{37}Ar one [19] (see sect. 3.5); moreover the GALLEX collaboration investigated *hot chemistry* effects spiking the detector with O(10000) atoms of ^{71}As [20]. It is worthwhile to remind the complexity and the difficulty of these experiments and the efforts that both collaborations did along the ultra-long data taking time to continuously refine the experimental procedures and to understand and reduce systematics. Due to the oscillation mechanism the neutrino interaction rate is 0.6 day^{-1} in GALLEX/GNO and 1.0 day^{-1} in SAGE. Hence at each extraction only a handful of atoms of ^{71}Ge atoms were available for the extraction.

3.2 ^{71}Ge counting and selection

This section describes in more detail the procedures adopted by GALLEX/GNO for the counting of ^{71}Ge decays and for the subsequent signal selection. The SAGE procedure, while conceptually similar, is quite different (details can be found in refs. [10,14]).

As anticipated in the previous section, the ν_e interactions in the target are tagged and counted by detecting the decay of ^{71}Ge. This is accomplished in GALLEX/GNO by means of ultra-low background miniaturized proportional counters (MPC) shown in fig. 1, developed in

[2] The active gallium target, *i.e.* the target from which the ^{71}Ge is actually extracted, is always 30 tons in GALLEX/GNO but can vary in SAGE from run to run.

MPIK Heidelberg [21] improving the original Davis design. ^{71}Ge decays by EC to ^{71}Ga, emitting characteristic X-rays and/or Auger electrons totaling 10.4 keV (K-capture, 87.7%), 1.1 keV (L-capture, 10.3%) or 0.1 keV (M-capture, 2.0%). An exposure time of 28 days, and accounting for all the extraction and counting efficiencies lead to the detection of 4.7 and 6.0 ^{71}Ge decays over a total counting period of about 6 months for GALLEX/GNO and SAGE, respectively.

The estimate of the ^{71}Ge decay rate is achieved in two separate steps: 1) an event-per-event selection based on pulse shape analysis (PSA); 2) a maximum-likelihood analysis on the event occurrence times (see sect. 3.3).

In the first step, events that are compatible with ^{71}Ge decays are selected, based on amplitude and pulse shape. In fact ^{71}Ge decays release a definite amount of energy in a X-ray/Auger cascade, totaling the binding energy of the captured electron. Events are selected as signal candidates if their reconstructed energy falls into two defined windows, centered at 1.1 keV (L-capture) and 10.4 keV (K-capture) respectively. M-capture decays release 0.1 keV and cannot be detected, due to the energy threshold of ~ 0.5 keV. The global acceptance of the energy cut is about 70%. It is limited by the energy resolution of the proportional counters and by the occurrence of degraded or partially-contained events, whose energy is underestimated.

Pulse shape is also considered to improve the rejection of background events. Genuine ^{71}Ge decays emit Auger electrons or fluorescence X-rays, which in turn can interact in the counter gas by photoelectric effect and produce low-energy secondary electrons. The range of electrons in the counter gas is very short (400 μm at 10 keV) so that ^{71}Ge events are typically very localized. Most background events are instead originated by γ-rays from environmental radioactivity: they mostly interact by Compton scattering and create energetic secondary electrons, having a much longer range in the counter gas. The 10–90% rise time (RT) of the charge pulse is strongly correlated with the extension of the region of the energy deposit: genuine ^{71}Ge decays have a shorter rise time than background events. The pulse shape discrimination of GALLEX consists in a cut on rise time only: events whose rise time is in given range are accepted as signal candidates. The cut has a typical acceptance of $\gtrsim 95\%$ and the selection range is derived from the routine calibrations of the counters with X-rays. The RT cut cannot handle those K-capture ^{71}Ge decays which produce a cascade of two X-rays, instead of a single photon: these events have a longer rise time (which is related to the difference in the drift time of the electrons from the two interaction sites to the central wire of the counter) and are hence accepted with a lower efficiency.

A more effective approach is used in GNO, which considers additional pulse shape parameters, other than rise time. Charge pulses are fitted with a semi-analytical empirical model which accounts for the response function of the electronics (*i.e.* the response to an ideal current δ-pulse) and for the charge collection function, due to the finite extension of the charge deposit. The charge collection function is modeled as a Gaussian, whose root-mean-square is a measure of the localization of the charge deposit. The model also accounts for the possibility of two independent and spatially-distant energy deposits (*e.g.* due to a X-ray cascade following a K-capture): two independent charge collection functions are considered in this case. The output parameters from the fit of the charge pulses are fed into a three-layer feed-forward neural network (NN), which returns one classifier between 0 and 1. The parameters used for the discrimination are the root-mean-square of the charge collection function, the RT (10–90%) and the χ^2 of the fit. In the case of double-ionization events, the ratio between the amplitudes of the charge collection functions and their distance in time are also fed as inputs to the NN. A sigmoid is used as the activation function of the individual neurons of the network. Since the L- and K-capture events have different signal shapes, two independent NNs are set up to process the two families. The NN training is performed by using event samples taken from ^{71}Ge/^{69}Ge calibrations (signal events) and from a dedicated run with a ^{137}Cs γ source, which is assumed to be representative of the environmental background. The acceptance of the NN-based selection is typically between 90 and 95% and hence comparable to the RT cut. The NN however exhibits a superior background rejection power with respect to the rise time cut (10–20% better) and a smaller uncertainty from the detector-related systematic effects.

3.3 Statistical treatment

The event time distribution is then fitted by an unbinned maximum likelihood (ML) procedure [9] to statistically discriminate ^{71}Ge signal counts against the residual background, which is constant in time. The data analysis is fundamentally the same for Chlorine, GALLEX/GNO and SAGE experiments.

Firstly, it is verified that only one decay component is present in the time distribution and that it has an half-life compatible with that of ^{71}Ge ($\tau = 16.49$ days) [22]. Then, the ML fit of the solar runs is performed, by keeping the amplitude of the decaying component and of the constant term as free parameters; the mean-life is fixed to the known value of ^{71}Ge.

A number of consistency checks were performed in GALLEX/GNO and in SAGE, based on the events energy and of the occurrence time, proving that the signal observed in the solar runs is consistent with the decay of ^{71}Ge [23,10,24]. The events detected during the first 50 days of counting (3τ of ^{71}Ge) have an energy distribution with peaks consistent with L- (1 keV) and K-captures (10 keV), as shown in fig. 2 (top). The ratio between the two peaks is also consistent with the expectations. The fitted mean-life of the decaying contribution is (16.6±2.1) days (see fig. 2, bottom), which is in agreement with the known value of 16.49 days [22].

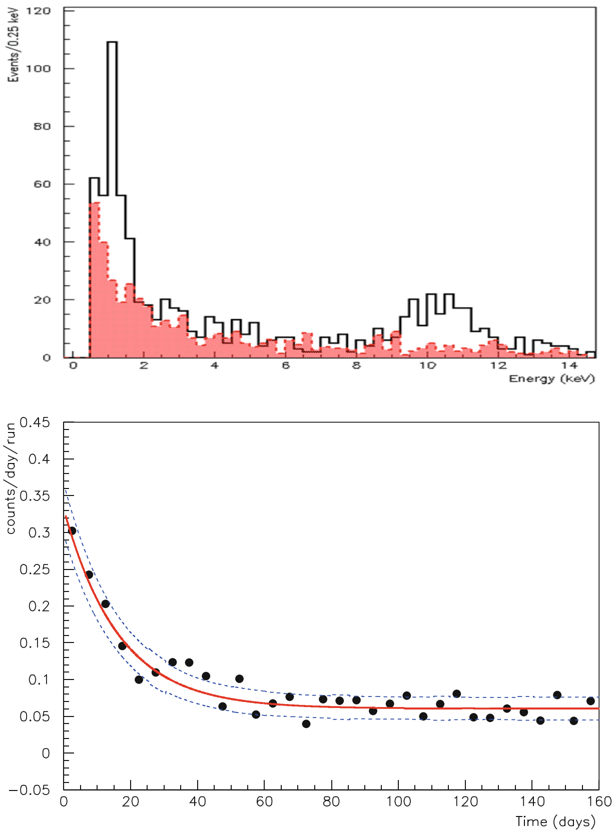

Fig. 2. Top: energy spectrum of the events in all the GNO solar runs. The black contour of the histogram encloses the fast counts that occurred during the first 50 days, graphically superimposed on the background spectrum (red) recorded after the first 50 days (normalized). Bottom: Counting rate of ^{71}Ge candidates *vs.* time for the 58 solar runs of GNO. Peripheral lines indicate $\pm 1\,\sigma$ envelopes: t_0 is start of counting just after the counter filled with the freshly extracted GeH_4 is inserted in the counting system.

3.4 Results

Table 1 reports values of $R^{\odot}_{\nu_e}$ measured by the two gallium experiments; GALLEX/GNO and SAGE measured over a time period of about 9 and 14 live time years, a value of $69.3 \pm 4.1 \pm 3.6$ [24] and $65.4^{+3.1}_{-3.0}(\text{stat})^{+2.6}_{-2.8}(\text{syst})$ [14] respectively. The gallium combined value is [14]

$$R^{\odot}_{\nu_e} = 66.1 \pm 3.1 \quad SNU. \tag{4}$$

The global error of gallium experiments is at the level of 4.5%. Figure 3 top and bottom graphically show the data sets of both experiments. For GALLEX/GNO all SNU-values are net solar production rates of ^{71}Ge after subtraction of 4.55 SNU for side reactions[3] [12,25] contributing with 1 SNU, and Rn-cut inefficiencies, and after correction of the geometrical modulation effect [24].

[3] All the reactions apart from ν_e interactions that produce ^{71}Ge and ^{69}Ge in the target: for GALLEX/GNO at LNGS of INFN the relevant components are high energy cosmic muons crossing the Ga target contributing to the ^{71}Ge production with 2.8 SNU, and ^{69}Ge produced by muons and ^{8}B neutrinos falsely attributed to ^{71}Ge.

The total systematic 1σ error amounts to $\sim$ 4.5 SNU for GALLEX (then reduced to $^{+3.7}_{-4.1}$ SNU after the latest GALLEX data reanalysis [26]), 2.5 SNU for GNO and $\sim$ 2.8 SNU for SAGE [14], respectively. We want to point out that the combination of the results of the two gallium experiments is delicate, because their systematics are different and because the latter varied during the very long data-taking periods; in GALLEX the main systematics were the counter efficiencies (4%), the pulse shape cuts (2.2%) the chemical yield (2%), the Rn-cuts inefficiency (1.2 SNU) [23]; GNO managed to reduce the first two contribution down to 2.2% and 1.3% respectively [24] by individually calibrating with $^{69}GeH_4$ gas, 51 counters out of 58, and by applying more refined neural network approach instead of pulse rise time cuts [27]. Until year 2002 the reported SAGE systematics were dominated by counter efficiencies (1.4 SNU) and counter gain stability (2.1 SNU): the latter has been then reduced. For GALLEX/GNO and SAGE the uncertainty on the target mass accounted for 0.5 SNU and 1.6 SNU, respectively.

In a cooperative effort of the SAGE and GNO collaborations 6 extractions samples from 6 extractions of a fraction of the SAGE gallium target were transported to the Gran Sasso laboratory for synthesis and counting at GNO. Six extractions of this type were made and the resultant solar neutrino capture rate was 64^{+24}_{-22} SNU [28], in good agreement with the overall result of the gallium experiments. The major purpose of this experiment was to make it possible for SAGE to continue the regular schedule of monthly solar neutrino extractions, while the ^{37}Ar experiment was ongoing and its extraction samples completely filled the SAGE counting system. As side benefits, this experiment proved the feasibility of long-distance sample transport in ultra-low background radiochemical experiments and familiarized each group with the methods and techniques of the other, thus cross-checking the procedures of GNO and SAGE.

As shown in fig. 4 and reported in table 1 GALLEX, and in particular the so-called GALLEX IV period, measured a significantly larger neutrino interactions rate than GNO. Also the SAGE measurements are more dispersed around the average in the first than in the second half of the exposure period. Hence the log-likelihood ratio test was performed on the whole GALLEX+GNO and SAGE, to test the compatibility of a varying interaction rate versus the null hypothesis of a constant one; confidence levels of 5.6% and $\sim$ 10% are found for the whole GALLEX/GNO and SAGE data sets, respectively; these values are surely on the low side but still acceptable.

To better understand if unrecognized background leaked in the GALLEX data, and after the successful implementation by GNO of the new algorithms for the pulse shape discrimination (PSD), a part of the GALLEX collaboration reprocessed the GALLEX raw data implementing a new PSD. The GALLEX$^{\text{PSD}}$ result $73.4^{+6.1}_{-6.0}(\text{stat})^{+3.7}_{4.1}(\text{syst})$, also reported in table1, is well compatible with the former GALLEX value $77.5^{+3.9}_{-4.3}(\text{stat})^{+3.9}_{-4.3}(\text{syst})$, and when combined with GNO (GALLEX/GNO) is $67.6 \pm 4.0(\text{stat}) \pm 3.2(\text{syst})$, well compatible with the previous $69.3 \pm 4.1 \pm 3.6$.

Table 1. $R^{\odot}_{\nu_e}$ as measured by gallium experiments.

	GALLEXGNO	GALLEX	GNO
Time period	05/1991 04/2003	05/1991 01/1997	05/1998 04/2003
Net exposure time [d]	3281 (8.98 yrs)	1594	1687
Number of runs	123	65	58
GALLEX/GNO [SNU]	$69.3 \pm 4.1 \pm 3.6$	$77.5^{+3.9}_{-4.3}$(stat)$^{+3.9}_{-4.3}$(syst)	$62.9{+}5.5_{-5.3} \pm 2.5$
L only [SNU]	70.9 ± 6.6	74.4 ± 10	$68.2^{8.9}_{8.5}$
K only [SNU]	67.8 ± 5.3	79.5 ± 8.2	$59.5^{6.9}_{6.6}$
GALLEX$^{\rm PSD}$ /GNO [SNU]	$67.6 \pm 4.0 \pm 3.2$	$73.4^{+6.1+3.7}_{-6.0-4.1}$	$62.9^{+5.5}_{-5.3} \pm 2.5$
	SAGE	first period	second period
Time period	01/1990 - 12/2007		
Net exposure time [y]	14		
Number of runs	168		
SAGE [SNU]	$65.4^{+3.1}_{-3.0}$(stat)$^{+2.6}_{-2.8}$(syst)		
L only [SNU]	$67.2^{+4.8}_{-4.6}$		
K only [SNU]	$64.0^{+4.1}_{-4.0}$		
SAGE + GALLEX$^{\rm PSD}$/GNO[SNU]	66.1 ± 3.1		

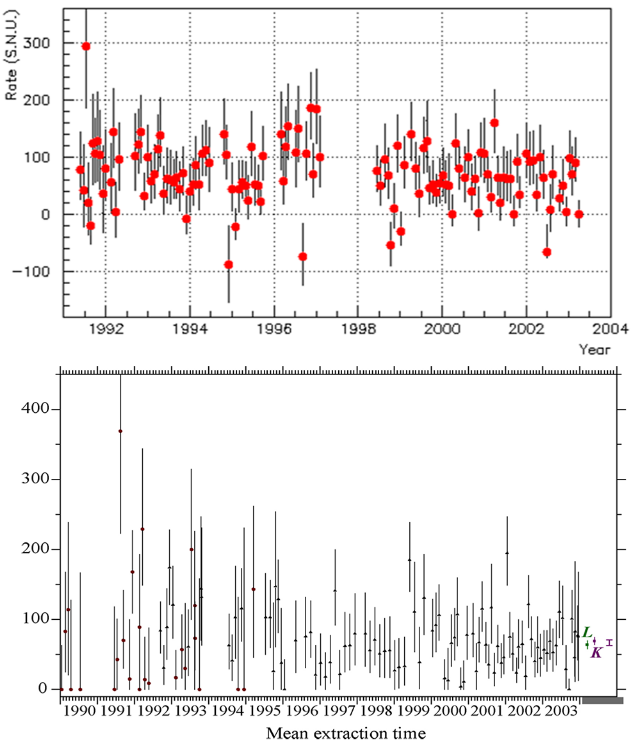

Fig. 3. Single run measurements of $R^{\odot}_{\nu_e}$ for GALLEX and GNO (top) and SAGE (bottom). GALLEX stopped in 1997 and GNO took over in 1998. The net solar neutrino production rate in SNU after subtraction of side reactions contributions [12,25] is plotted. Error bars are $\pm 1\,\sigma$, statistical only. For SAGE only solar runs up to 2003 are shown.

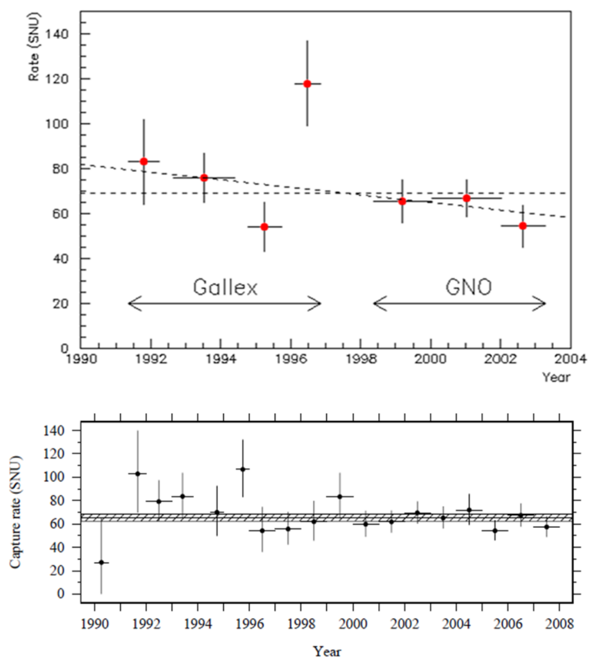

Fig. 4. GALLEX/GNO (top) and SAGE (bottom) measured values of the solar neutrino interaction rate one year binned for SAGE, while for GALLEX/GNO the binning varies and is about 1 year.

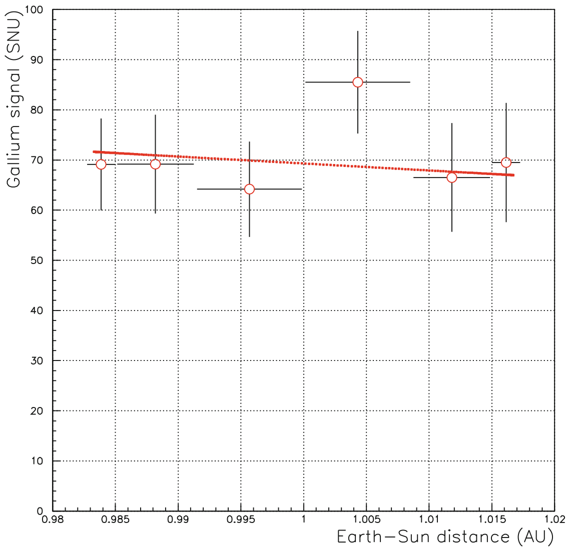

Fig. 5. Measured values of $R^{\odot}_{\nu_e}$ GALLEX/GNO bimonthly binned. The line indicates the expected rate variation due to purely geometrical ($1/d^2$) reasons.

When looking for time modulation in solar neutrino interactions at Earth the first search is for day-night or seasonal variations. While day-night variations are not accessible to gallium radiochemical experiments as the exposure time is ~ 30 days, seasonal variations can be studied, although this search is limited by statistics. Figure 5 shows the GALLEX/GNO whole data set bi-monthly binned; no evidence of seasonal modulation appears. The expected +2.3 SNU for $\Delta(R_W - R_S)$ due to the Earth orbit ellipticity has been already removed. The seasonal difference Winter-Summer[4] $\Delta(R_W - R_S)$ of $R^{\odot}_{\nu_e}$ measured by Gallium experiments is $4.2^{+6.2}_{-6.1}$ and -7.6 ± 9, for SAGE and GALLEX/GNO respectively; in both cases it does not significantly differ from zero, as expected for LMA. To investigate if the measured solar neutrino capture rate shows a time variability as suggested f.i. by [29,30] both experiments performed dedicated search for possible time modulations [14,31] using different methods (Lomb-Scargle analysis, Maximum Likelihood, Nw^2).

The Lomb-Scargle periodograms of both GALLEX/GNO and SAGE are statistically consistent with the expectations of a constant interaction rate.

3.5 The gallium-ν_e absorption cross section

Both experiments were irradiated with strong artificial neutrino sources. GALLEX irradiated twice its target in 1994 and in 1996 with a calibrated ^{51}Cr source of strength 63.4 ± 0.5 PBq and 69.1 ± 0.6 PBq, respectively [18]. SAGE irradiated a fraction of its metallic Ga target (13.1 tons) first with a 19.1 ± 0.2 PBq ^{51}Cr source, then in 2003-2004 with a 1.5 PBq ^{37}Ar artificial neutrino source [19]. ^{51}Cr undergoes EC-decay with an half-life of 27 days to both the ground and the first excited state of ^{51}V emitting neutrinos of 750 keV (90%) and 430 keV (10%), while ^{37}Ar decays by EC to ^{37}Cl ground state emitting a 814 keV neutrino. The artificial neutrino sources produced ^{71}Ge nuclei at a rate about 20 times larger than the solar neutrinos. In the assumption of proportionality between the (p,n) forward scattering cross-section and the Gamow-Teller strength, the theoretical ν_e capture cross section $\sigma = 58.1^{+2.1}_{-1.6} \cdot 10^{-46}\,\mathrm{cm}^2$, and the contribution of the first two excited states of ^{71}Ge in the ^{71}Ga-^{71}Ge transition is found to be 5% [32]. Averaging the two ^{51}Cr GALLEX exposures respectively, the ratio of the observed to expected interaction rate (R) is $R = 0.88 \pm 0.08$ [26]. When the two SAGE source experiments are included, the weighted average value of the ratio of the two experiments is $R = 0.87 \pm 0.06$: it is about 2σ away from unity, and the χ^2 compatibility test of the four source experiments to $R = 1$ gives a CL of 5.3%. Any possible *hot chemistry* effect was ruled out in GALLEX by the crucial ^{71}As test, which proved the tank-to-counter yield to be (100.0 ± 1.2)% [20]. If instead the contribution of the excited states to the expected rate is assumed to be zero, R is 0.92 ± 0.06 and the goodness of fit to $R = 1$ is 21%. The low R values of the Ga experiments may be explained by the disappearance of electron neutrino into sterile neutrinos [33]; this hypothesis will be verified by the forthcoming SOX experiment [34], by irradiating Borexino with an artificial neutrino source.

[4] Winter here is defined as the $\pm1/4$-year interval centered around January 7th, and summer the $\pm1/4$-year interval centered around July 5th.

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