

Retrospect of GALLEX/GNO

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Abstract. After the completion of the gallium solar neutrino experiments at the Laboratori Nazionali del Gran Sasso (GALLEX, GNO), we shortly summarize the major achievements. Among them are the first observation of solar pp-neutrinos and the recognition of a substantial (40%) deficit of sub-MeV solar neutrinos that called for ν_e transformations enabled by non-vanishing neutrino masses. We also inform about a recent complete re-analysis of the GALLEX data evaluation and reflect on the causes for the termination of GNO. From our gallium data we extract the e-e survival probability P_{ee} for pp-neutrinos after subtraction of the ^8B and ^7Be contributions based on the experimentally determined ^8B - (SNO/SK) and ^7Be - (Borexino) neutrino fluxes as $P_{ee}(\text{pp only}) = 0.52 \pm 0.12$.

1. Introduction

The Gallium solar neutrino experiments at the Laboratori Nazionali del Gran Sasso have been terminated for external non-scientific reasons. This triggers a short retrospect of the achievements of GALLEX and GNO (Section 2). In Section 3 we report on a recent update that is based on data that were impossible to acquire before completion of the low rate measurement phase (solar runs). After some reflections on the causes for the termination of the gallium experiments at Gran Sasso (Section 4), I give a first quantitative estimate of the separate pp solar neutrino production (Section 5). This ultimate goal of GALLEX can be approached after the first results from BOREXINO allow subtracting the ^7Be -neutrino contribution from the gallium results.

2. Retrospect of GALLEX /GNO

GALLEX and GNO have recorded solar neutrinos with energies above 233 keV via the inverse EC reaction $^{71}\text{Ga}(\nu_e, e^-)^{71}\text{Ge}$ in a 100-ton gallium chloride target (containing 30.3 tons of gallium) between May 1991 and April 2003 [1][2][3]. The key features are summarized in Figure 1. Of utmost importance is the low energy threshold. 98+ % of all solar neutrinos are sub-MeV (pp: ~91%, ^7Be : ~7%). The pp-neutrino flux is coupled to the solar luminosity. It is a fundamental parameter that must definitely be measured, as precisely as possible. Stringent limitations (or observation) of departures from the standard solar model can be obtained if the flux of pp-neutrinos is deduced, provided that, as it is now the case, neutrino properties are properly folded in. Below ~1-2 MeV, the vacuum oscillation domain takes over from the matter oscillation domain at > 2 MeV.

The milestones and key references are given in Table 1 (PLB = Physics Letters B). The solar neutrino recordings cover more than a full solar cycle (1991-2003), with a break in 1997. In addition, very important demonstrations of the reliability of the radiochemical method in general and of the GALLEX detector in particular have been provided with the ^{51}Cr source experiments and with the Arsenic 71 tests.

The GALLEX collaboration announced the first observation of solar pp-neutrinos at ‘Neutrino 92’ in Granada on June 8th, 1992. Subsequently, the GALLEX recordings (till 1997) confirmed both the presence of pp-neutrinos [1] and a significant deficit ($\approx 40\%$) in the sub-MeV neutrino induced ^{71}Ge production rate [2]. At that time, this was the strongest indication for neutrino transformations on the way between the solar core and the Earth, implying non-zero neutrino mass and non-standard physics [4][5]. The subsequent GNO observations have improved the quality of the data, added important restrictions on the presence of possible time variations, and substantially reduced the total error on the charged current reaction rate for pp-neutrinos as measured by the inverse EC reaction on gallium [3]. Without radiochemical gallium detectors, the majority (92%) of all solar neutrinos would still remain unobserved.

Gallium experiments at LNGS have provided a long time record of low energy solar neutrinos and determined the bulk production rate with an accuracy of ± 5.5 SNU (Table 2). This is based on 123 solar runs, 65 from GALLEX and 58 from GNO (Figure 2). The result and its precision will remain without competition from upcoming low-threshold real-time experiments for many years to come. Recorded is a fundamental astrophysical quantity, the neutrino luminosity of the Sun. In the astrophysical context, the gallium results shed light on the individual contributions of the PPI, PPII and CNO cycles to the solar luminosity and on the agreement of the energy production derived from the photon- and from the neutrino luminosity respectively [3].

Radiochemical experiments are first generation experiments. Opposite to real-time experiments, they provide no spectral or directional information. The statistical errors equal now the intrinsic systematic errors. This success implies their end. However, they have been crucial in paving the way into the excitement of the third millennium!

3. A recent update

The largest components of the systematic errors are the absolute efficiencies of the individual miniaturized low-level gas proportional counters. To maintain the extremely low background rates (~ 1 count per month) internal calibration that requires high ^{71}Ge activities was prohibited as long as the counters were used in the solar neutrino runs. However, after the completion of the solar runs such calibrations (using $\sim 10^5$ Ge-decays per counter) became possible and were done for the old counters

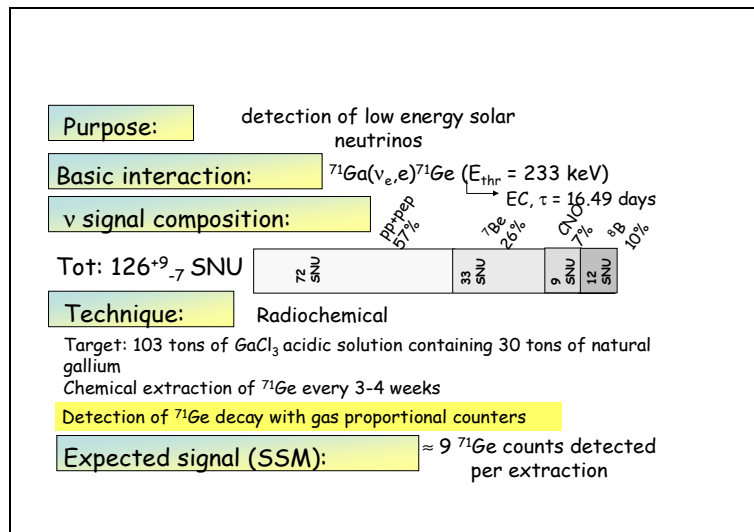


Figure 1. Scheme of the Gallium experiments

1986 - 1990			Construction of the detector
May 1991 – May 1992	GALLEX I data taking	PL B285 (1992) 376	
	15 Solar runs, 5 Blanks	PL B285 (1992) 390	
	$83.4 \pm 19 \text{ SNU}$		
Jun 1994 – Oct 1994	1st ^{51}Cr source experiment	PL B342 (1995) 440	
Oct 1995 – Feb 1996	2nd source ^{51}Cr experiment	PL B420 (1998) 114	
Feb. 1997	End of Solar Data taking	PL B447 (1999) 127	
	GALLEX Final Result		
	1594 days – 65 runs: $77.5 \pm 7.7 \text{ SNU}$		
Feb 1997 – Apr 1997	Test of the detector with ^{71}As	PL B436 (1998) 158	
Apr 1998 – Apr 2003	GNO data taking	PL B490 (2000) 16	
		PL B616(2005) 174	

Table 1. Milestones for GALLEX and GNO.

GNO	$62.9 \pm^{6.0}_{5.9}$ SNU
GALLEX	$77.5 \pm^{7.6}_{7.8}$ SNU
GALLEX+GNO	69.3 ± 5.5 SNU
SAGE	$66.9 \pm^{5.3}_{5.0}$ SNU

Range of SSM predicted rates:	
No oscillations:	122 – 131 SNU
With oscillations (global fit)	68 – 72 SNU

Table 2. Final results

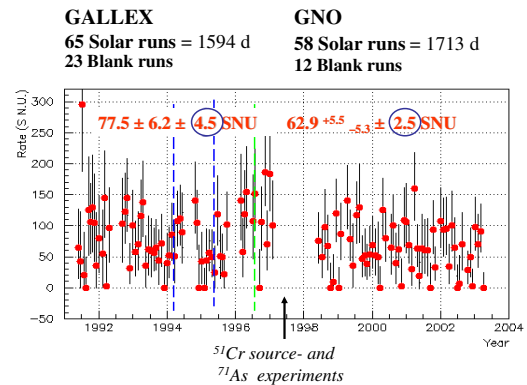


Figure 2. Individual solar runs

used in GALLEX. This triggered a complete re-analysis of the GALLEX data [6]. In addition to the efficiency error reduction, two other effects have been included:

- Improved Rn-cut efficiency after completion of the respective multi-year low-rate measurement.
- Full pulse shape analysis of the counter pulses instead of rise time analysis.

Among the four GALLEX data taking periods, by far the largest change is for GALLEX IV. This is the period that had created some concern because of a $+2.5\sigma$ deviation from the mean. Now this has reduced itself to $+1\sigma$. The integral updated results are given in Table 3; a full publication is in preparation.

GALLEX	$77.5 \pm^{7.6}_{7.8}$ SNU
re-evaluated	$73.1 \pm^{7.1}_{7.3}$ SNU
GNO (unchanged)	$62.9 \pm^{6.0}_{5.9}$ SNU
GALLEX+GNO	69.3 ± 5.5 SNU
re-evaluated	67.5 ± 5.1 SNU

Table 3. Updated Results

Partitioning of the Gallium Cake

(Experiments, SSM and LMA)

	SNU	P_{ee}	Experim.
measured	68 ± 5		GX/GNO
$^7\text{Be}_{\text{exp}}$	22 ± 7	0.68 ± 0.20	Borexino
$^8\text{B}_{\text{exp}}$	4 ± 1	0.33 ± 0.08	SK + SNO
$^{13}\text{N}, ^{15}\text{O}$	$4.5^{+1.3}_{-1.3}$	~ 0.5 (assumed)	-
pep	$1.5 \pm .5$	~ 0.5 (assumed)	-
pp only	36 ± 8	0.52 ± 0.12	Gallium

Table 4. Deduction of the pp-flux

Also the Cr-source data have been reanalyzed with new efficiencies and an improved solar subtraction to include also the GNO data (see Table 2). This Cr-source update yields a reduction of the ratio $R = \text{activity}_{\text{measured}}/\text{activity}_{\text{expected}}$ from $93 \pm 8\%$ [7] to $88 \pm 8\%$ (1σ). The expectation value for ground state transitions only is $95 \pm 1\%$ [8]. Our ^{71}As experiments exclude any Ge-yield errors above 1%. Consequently, the excited state contribution is probably close to zero, instead of $(5 \pm 3)\%$ as estimated by Bahcall. This is also supported by the SAGE Cr-source result. If this is true, then the ^{71}Ge production rate prediction on Ga (without neutrino oscillations) must be reduced by ~ 2 SNU from ^{71}Be -neutrinos, from 34.8 SNU to 32.7 SNU (for pp-neutrinos, there is no change).

4. The causes for the termination of the Gallium experiments at LNGS

It has never been questioned that GALLEX/GNO has been a great success. This would not automatically justify a continuation after the main goals have been achieved. However, as long as real-time pp-neutrino detection was (and still is) a long way to go, there existed very important reasons to continue GNO:

- Continuous pp-neutrino monitoring is an astrophysical necessity.
- pp-neutrino observations simultaneously with Borexino real-time beryllium neutrino observations would help to check on non-standard scenarios (time variations).
- Further neutrino source experiments would improve the knowledge of relevant cross sections.

Still, in 2004 it was decided by INFN that the GNO experiment should be terminated since it constitutes a safety risk which prevents the release of restrictions imposed on the Laboratori Nazionali del Gran Sasso (LNGS) by national safety authorities. This was not true. GALLEX/GNO (in Hall A) never spilled a single drop of liquid. The spill occurred in Hall C (Borexino). Ironically, GALLEX introduced the double spill tray safety conception in 1986, almost 20 years before it now became mandatory for the Laboratory. I quote here 'Physics Today' as an independent observer:

Quote: „The Gallium Neutrino Observatory (GNO) is the price that Italy's underground lab is paying to get back on its feet after a small chemical spill nearly two years ago” [9].

I wish to state with due respect that the GALLEX corpse feeded Borexino for survival.

GNO17, the last regular (semi-annual) GNO meeting was held at LNGS on April 6, 2005. On February 28, 2006 a *Final Celebration Ceremony for GALLEX/GNO* ended a successful fifteen year long period that had started with the *Inauguration Ceremony* on November 30, 1990. In April 2007, the gallium (chloride) was sold to Recapture Metals Inc., Ontario, Canada.

5. Oscillation parameters and the partitioning of the Gallium cake

If the LMA(MSW) solution is the correct explanation of the SNO/SK data, then vacuum oscillations must dominate below 1 MeV and the mixing angle is estimated as $\theta = 32 \pm 1.6$ degrees [10].

The first preliminary results from the BOREXINO experiment on the flux of solar ^7Be neutrinos make it now possible to deduce the pp-neutrino flux separately. We extract from our data the e-e survival probability P_{ee} for pp-neutrinos after subtraction of the ^8B and ^7Be contributions based on the *experimentally* determined ^8B -(SNO/Superkamiokande) and ^7Be -(BOREXINO) neutrino fluxes as $P_{ee}(\text{pp only}) = 0.52 \pm 0.12$ (Table 4).

The results imply the experimental verification of the solar model and of the neutrino oscillation mechanisms at sub-MeV energies that are otherwise inaccessible.

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