THE GALLIUM SOLAR NEUTRINO EXPERIMENT GALLEX

Heidelberg-Karlsruhe-Milano-Munchen-Nice-Rehovot-Roma-Saclay Collaboration

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Abstract

The low threshold (233 keV) of the neutrino capture reaction $^{71}Ga(\nu_e,e^-)^{71}Ge$ is a real chance for the detection of solar neutrinos , particularly those coming from the pp reaction. The GALLEX experiment will measure the solar neutrino flux by counting the ^{71}Ge atoms produced in a 30 ton gallium target in the form of a $GaCl_3$ solution. A calibration will be done with a ^{51}Cr source which emits 751 keV neutrinos. The detector will be set up in the Gran Sasso Underground Laboratory (Italy) . The expected result will allow a better understanding of solar models and to discriminate between solar models problems and possible neutrino oscillations .

1. Introduction.

The so-called solar neutrino puzzle consists in the discrepancy between experimentally observed solar neutrino flux and solar models theoretical predictions . The latest result of the only experiment which has ever been performed to detect solar neutrinos , the chlorine experiment [1] , is now 2.0 ± 0.3 SNU (1 SNU corresponds to 10^{-36} capture / atom / second) while the theoretical expectations of the standard solar model give [2] 5.8 ± 2.2 SNU (3σ limit) . However the main criticism to the chlorine experiment is that the threshold for ν_e capture by ^{37}Cl in the reaction $^{37}Cl(\nu_e, e^-)^{37}Ar$ is 814 keV which corresponds only to the tail of the solar ν_e spectrum . Two major reasons are generally invoked to explain the chlorine experiment results : either there are some problems with the solar models or there are neutrino oscillations .

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In order to try to solve this puzzle a new radiochemical experiment has been proposed some time ago , involving the gallium as a target [3,4]. The ^{71}Ga is sensitive to solar neutrinos by the capture reaction

$$\nu_e + {}^{71}Ga \longrightarrow {}^{71}Ge + e^- \qquad (1)$$

The threshold (233 keV) is very convenient to detect a large part of the solar ν_e spectrum , particularly the ν_e coming from the pp fusion reaction. The newly proposed experiment (GALLEX) needs 30 tons of gallium in the form of $GaCl_3$. In the frame of the standard solar model 1 atom of ^{71}Ge should be produced each day . The produced ^{71}Ge atoms have to be extracted and counted each two weeks ($T_{1/2}$ = 11.43 days). Such techniques have already been developed and the experiment has been proved to be feasible . Due to the requirement of a low level background site it is intended to set up the detector in the Gran Sasso Underground Laboratory (120 km from Rome in the Apennine mountains) . Moreover it is planned to calibrate our detector with a 800000 Ci ^{51}Cr source which provide monochromatic ν_e (751 keV) .

In this paper we first recall briefly the standard solar model predictions and the neutrino oscillation problem . We then describe our proposed gallium experiment : extraction , counting , background , calibration with a ^{51}Cr source , schedule , with some details . Finally we give what would be the implications of the results on solar physics and/or neutrino oscillation physics . More details on this experiment can be found in reference [5].

2. The solar neutrino flux in the standard solar model (SSM).

The standard solar model is described elsewhere [6]. We just recall here the origin of the neutrinos coming from the sun , the predictions for the corresponding flux and for the neutrino capture cross sections .

Most of the energy produced in the sun comes from the pp fusion reaction chain :

$$p + p \longrightarrow {}^2H + e^+ + \nu_e \quad \text{(2 times)} \qquad \nu_{pp}$$

$$^2H + p \longrightarrow {}^3He + \gamma \quad \text{(2 times)}$$

$$^3He + {}^3He \longrightarrow {}^4He + p + p$$

or $$^3He + {}^4He \longrightarrow {}^7Be + \gamma$$

Electron or proton capture on the ^7Be may also give :

$$e^- + {}^7Be \longrightarrow {}^7Li + \nu_e \qquad \nu_{Be}$$

$$p + {}^7Be \longrightarrow {}^8B + \gamma$$

$$\hookrightarrow {}^8Be^* + e^+ + \nu_e \qquad \nu_B$$

A small fraction comes from the pep reaction :

$$p + e^- + p \longrightarrow {}^2H + \nu_e \qquad \nu_{pep}$$

There is also a small contribution (1.5 %) of the CNO cycle in the total fusion energy liberated.

The predictions of the standard solar model concerning the neutrino flux at the earth level are given in Fig. 1a where the six main contributions are represented . The integrated flux value is given for each neutrino source in Table 1 . In Table 1 are also shown the predictions for the neutrino capture cross sections in ^{71}Ga , in SNU's (see for example ref. [7] for neutrino capture cross sections) . The values are the ones recently published by Bahcall et al. [2] and take into account recent calculations of ^{71}Ge halflife (11.43 days) and Q_{EC} value (233.2 keV) [8]. These predictions do not take into account the contributions for $^{71}Ge^*$ excited states which have been estimated to be of the order of 10 % of the contribution for the ^{71}Ge ground state [9]. (The decay scheme of ^{71}Ge is represented in Fig. 1b where energies of ν_{pp} , ν_{Be} and ν from ^{51}Cr are also shown).

Table 1 : Solar neutrinos flux (in $\nu/cm^2/s$) and gallium capture rates (in SNU) for the different sources in the sun.

Source	Flux [6]	Energy spectrum (MeV)	Capture rate
pp	$6.07\ 10^{10}$	0.-0.420	67.1
pep	$1.50\ 10^{8}$	1.440	2.4
^{7}Be	$4.3\ 10^{9}$	0.862 (90%) , 0.383 (10%)	30.3
^{8}B	$5.6\ 10^{6}$	1.-14.	1.5
^{13}N	$5.0\ 10^{8}$	0.-1.20	2.6
^{15}O	$4.0\ 10^{8}$	0.-1.73	3.7
Total			107.6

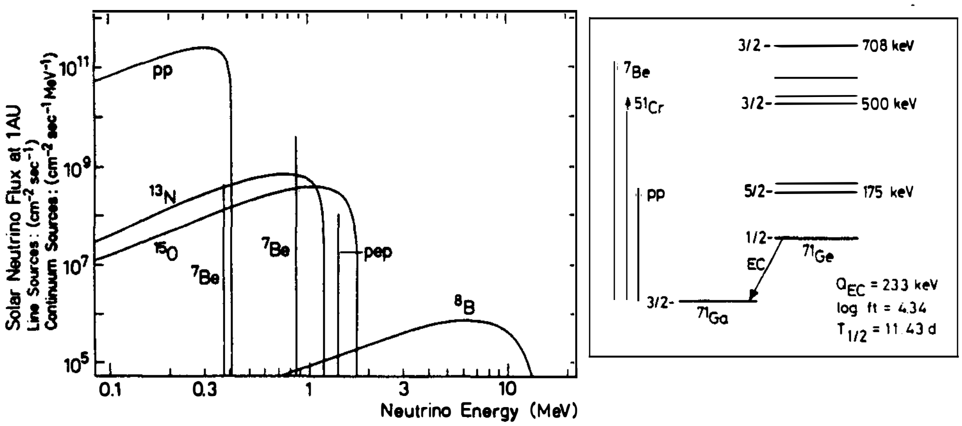

Figure 1 : a) Solar neutrino spectrum in the SSM - b) ^{71}Ge decay scheme.

3. Neutrino oscillations.

The hypothesis of neutrino oscillation between their different flavours (ν_e , ν_μ , ν_τ) is now well known (see for example ref. [10]). It is based on the idea that neutrinos , eigenstates of the weak interaction, are not eigenstates of the mass but linear combinations of ν_1 , ν_2 and ν_3 which are the eigenstates of the mass :

$$|\nu_l> = \Sigma\ U_{li}\ |\nu_i> \qquad l=e,\mu,\tau \quad i=1,2,3$$

The fraction of flavour m neutrinos observed at a distance x from the flavour l neutrinos source can be written :

$$P(\nu_l \to \nu_m) = \Sigma\ U_{li}{}^2.U_{mi}{}^2 + \Sigma\ U_{li}.U_{mi}.U_{lj}.U_{mj}\ \cos(2\pi x/l_{ij})$$

where $l_{ij}(m) = 4\pi p_\nu/|m_i{}^2-m_j{}^2| = 2.48\ p(MeV/c)\ /\ |\Delta m^2|\ (eV^2)$

is the oscillation length.

The distance between the sun and the earth is $L = 1.5\ 10^{11}$ m and we may hope to be sensitive to Δm^2 until about 10^{-11} eV^2 which is much more than all known results on limits to neutrino oscillations (for recent results see [11]) .

If we consider a mixture of two flavours only the U matrix is a rotation matrix (angle θ) and we have :

$$P(\nu_e \to \nu_e) = 1 - \sin^2 2\theta.\sin^2(1.27\ \Delta m^2\ L\ /\ p_\nu) \qquad (2)$$

4. The gallium experiment.

a) history.

The first idea for using gallium for the detection of solar neutrinos was suggested by Kuzmin [3]. The first proposal for such an experiment is due to Bahcall et al. [4] in 1978 who requested 50 tons of gallium . A pilot experiment with 1.3 ton of gallium was done at Brookhaven to show the feasability of the extraction of small quantities of ^{71}Ge . A proposal by a Brookhaven-Heidelberg-Rehovot-Philadelphia-Princeton Collaboration was written in 1981 [12]. This collaboration was dismantled in 1983 due to lack of money . A new collaboration was built in 1984 , with mainly European Laboratories [13].

b) design.

The 30 tons of gallium (39.6 % of ^{71}Ga and 60.4 % of ^{69}Ga) in form of a concentrated $GaCl_3$-HCl solution are placed in a large tank . The ^{71}Ge produced in the neutrino capture reaction (1) form the volatile $GeCl_4$ compound which is swept out of the solution by circulating air through the tank . The gas flow is passed through gas scrubbers where $GeCl_4$ is absorbed in water . The $GeCl_4$ is then extracted into CCl_4 , back extracted into tritium-free water and finally reduced to the germane GeH_4 gas by using KBH_4 . The germane is introduced with xenon in a small proportionnal counter where the number of ^{71}Ge atoms is determined by observing their radioactive decay .

c) extraction of the ^{71}Ge.

The feasability of the extraction has been proved in a pilot experiment done at Brookhaven with 1.3 ton of gallium (see fig. 2a) . More than 30 runs have been performed by introducing small amounts (a few mg down to 100 µg) of stable Ge carrier , as well as runs in which the ^{71}Ge was produced in the $GaCl_3$ by cosmic rays or by a neutron source , or by decay of ^{71}As.

An example of germanium extraction from the pilot tank is shown in fig. 2b where more than 99 % of the 2 mg added to the $GaCl_3$ solution before sweeping have been extracted in 1.2 day . The conclusion is that the entire chemical process (extraction and conversion into GeH_4) can be carried out with more than 95 % overall yield.

In the final experiment it is planned to extract the produced ^{71}Ge every two weeks , taking one day for extraction.

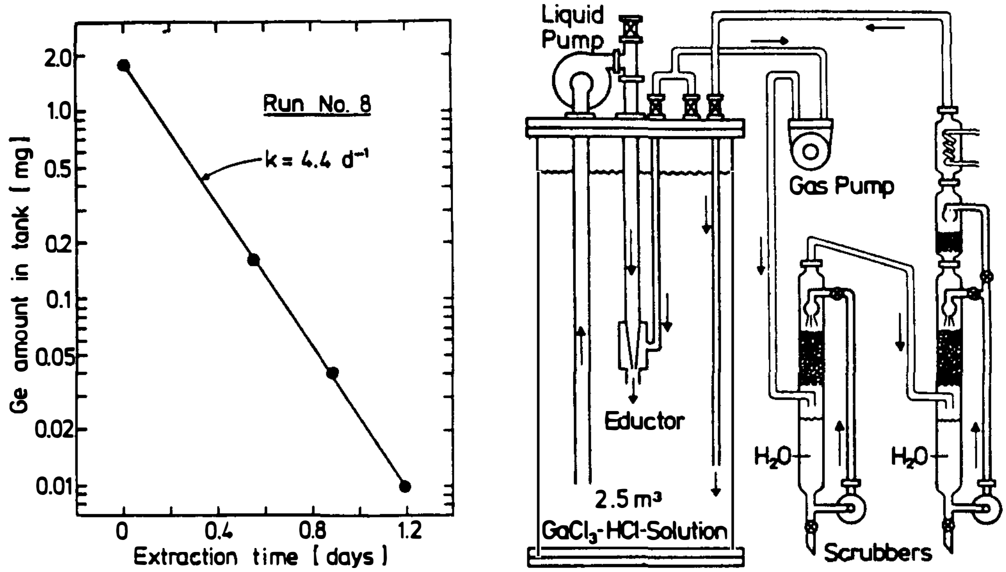

Figure 2 : Extraction system in the pilot experiment and result of an extraction run.

d) counting of the ^{71}Ge.

In the frame of the standard solar model and with the expected capture rate about 1 ^{71}Ge atom is produced each day in the tank (1 SNU corresponds to 8.7 10^{-3} capture/day in the 30 t detector). A counting system able to measure such low decay rates has been developed by the Heidelberg group . ^{71}Ge decays by electronic capture and the energy deposition from Auger electrons and X rays emitted results mainly in a spectrum with an L peak at 1.2 keV and a K peak at 10.4 keV . The miniaturized proportional counters are built with ultrapure materials . They are placed in an anticoincidence shield with NaI and plastic scintillation detectors , completed by heavy passive shielding with lead and iron . The counter background is then of the order of 1 count per day . But the pulse shape of this background (materials radioactivity , external γ rays , electronic noise) is different of that of the ^{71}Ge decay [5] and a pulse shape analysis using a transient digitizer allows to reduce the background level . Fig. 3 displays the results of a 51.5 day counter background measurement obtained with one of the best counters. G*I , a quantity characterizing the pulse shape , is plotted versus the energy for each count. The boxes represent the regions where 95 % of all ^{71}Ge events with energies in the L and K peak windows are located . The background obtained is .08 (.04) count per day in the L (K) peak and the corresponding counting efficiencies are respectively 28 and 43 % for the L and K peaks.

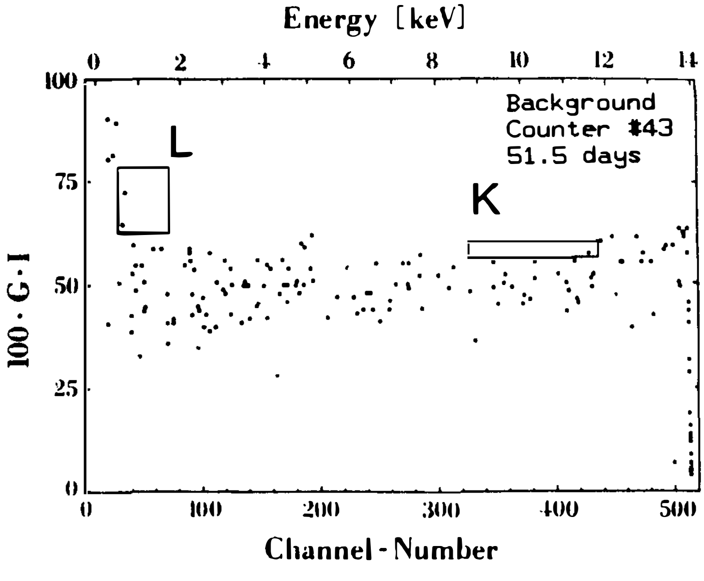

Figure 3 : Proportional counter background measurement.

e) <u>background due to ^{71}Ge produced by other sources than solar neutrinos.</u>

^{71}Ge atoms may be produced in the 30 t detector by other sources than solar neutrinos . This background consists mainly in the reaction ^{71}Ga(p,n)^{71}Ge . The interacting protons come from :

i) cosmic ray muons interactions . In the Gran Sasso Laboratory (shielding depth $\simeq$ 3500 m water equivalent) we expect .01 atom per day .

ii) (α,p) reactions where α come from radioactive decays of U , Th and Ra present in the $GaCl_3$ solution . Low level of these radioactive atoms can be obtained for large $GaCl_3$ quantities and give less than .01 ^{71}Ge atom per day.

iii) (n,p) reactions induced by neutrons from the surrounding rock. 0.8 n/cm^2/day would give .006 ^{71}Ge atom per day. Preliminary measurements [14] give an upper limit of 2.6 n/cm^2/day. It can be measured more precisely by using the reaction ^{40}Ca(n,α)^{37}Ar where ^{37}Ar atoms can be counted. If the level was too high an additional 25 cm water shielding around the detector would reduce this background by an order of magnitude.

The total background is then less than a few percent and can be monitored by the reaction ^{69}Ga(p,n)^{69}Ge which has a large cross section and which can be counted in the same way as the ^{71}Ge.

f) calibration with a ^{51}Cr source.

There are still uncertainties about the cross section contribution from the two excited states in ^{71}Ge at 175 and 500 keV (which can be populated by allowed Gamow-Teller transitions) whose contribution is about 10 % of the ground state one [9] (see Fig. 1b) . In order to complete information about the ^{71}Ga neutrino capture cross section and to have an overall consistency check of the detector a calibration experiment using an artificial ^{51}Cr source is planned as a full part of the experiment. ^{51}Cr decays ($T_{1/2}$ = 27.7 days) by the electronic capture reaction ^{51}Cr(e$^-$,ν_e)^{51}V . It emits monoenergetic neutrinos : 90 % at 751 keV and 10 % at 431 keV . The 751 keV ν_e can populate the two excited states at 175 and 500 keV (see Fig. 1b) . An excess of the measured ^{51}Cr signal above the ground state contribution could be attributed to these excited states .

The characteristics of the source are the following : 100 kg of chromium powder are irradiated in Siloė (Grenoble) and Osiris (Saclay) during 2 months , giving an activity of 800000 Ci , activity necessary to perform a significant experiment . The source is then placed inside the $GaCl_3$ tank during 2 months , with a ^{71}Ge extraction each 2 weeks . The expected sensitivity is 18-20 % after one such run and 10 % after 4 runs (1 year).

g) schedule.

In 1985 the proposals are being submitted to respective German , French and Italian authorities and to Gran Sasso committee . The approvals are expected before the end of the year and the installation could begin immediately . The completion for gallium acquisition could then be at the end of 1986 . 2 years of running (50 extractions) are necessary to obtain 10 % statistical error on the number of ^{71}Ge produced atoms . These 2 years and 1 year of calibration could be planned in 1987-1988-1989 and a first result could be given at the end of 1989.

5. Interpretation of the forthcoming result.

The interpretation of the forthcoming result depends on the result itself :

- between 100 and 130 SNU the standard solar model is probably correct and we can exclude neutrino oscillations with a large mixing.
- below 70 SNU the neutrino oscillation hypothesis is the most probable since no actual solar model predicts a value lower than 70 SNU which corresponds to "extreme models" i.e. models with energy generation in sun by fundamental pp reactions only .
- between 70 and 100 SNU the chlorine result and the gallium result should be combined to give a reliable explanation .
- above 130 SNU the field is open for models such the model with quarked nuclei which can predict until 250 SNU [15].

To illustrate this we display in fig. 4 the ^{37}Ar production rate in the chlorine experiment versus the ^{71}Ge production rate in the gallium experiment . The two horizontal lines correspond to the chlorine result with 2 σ [1]. The circle corresponds to the standard solar model (SSM) . The dashed line corresponds to different solar models and particularly the turbulent diffusion mixing model which predicts a very small flux of ν_B [16]. The cross corresponds to the minimum rate (neutrino production by pp reaction only). The full line gives the prediction of the SSM in case of neutrino oscillation (with $\Delta m^2 > 10^{-8}$ eV^2) with a mixing varying along the line . The two marked points along the line correspond respectively to the two neutrino mixing and three neutrino mixing with the maximum value of the mixing parameter . If Δm^2 is below 10^{-8} eV^2 the situation is a little more complicated since the average value of the $\sin^2(1.27\ \Delta m^2\ L / p_\nu)$ term in equation (2) depends on Δm^2 but definite conclusions can still be drawn (see [17]).

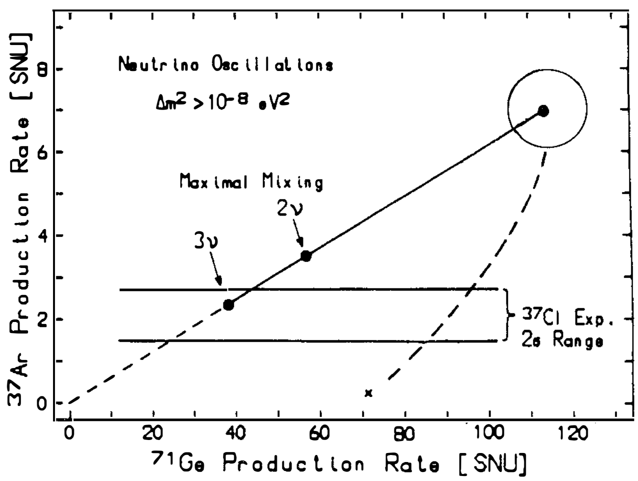

Figure 4 : ^{37}Ar observed production rate versus ^{71}Ge production rate (see text).

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