GALLEX: First Results and Implications for Neutrino Physics

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Abstract

The GALLEX experiment, located in the Gran Sasso underground laboratory, completed its first measurements of the production rate of Ge-71 from Ga-71 due to solar neutrinos. The GALLEX detector is uniquely sensitive to the low energy neutrinos produced by proton-proton fusion in the center of the sun. From these first measurements, which cover a period of exposure of 295 days, a rate of 83 +/- 19 (stat.) +/- 8 (syst.) (1 sigma) SNU [1 x 10^(-36) captures / target atom - second] is reported. This initial result is two standard deviations below the solar model calculations. The implications of a neutrino deficit in terms of neutrino flavor oscillations are summarized.

1. Introduction

A significant change in the experimental state of solar neutrino detection now arises with the online status of the two newest detectors based on gallium -- GALLEX [1] (Gallium Experiment at the Gran Sasso) and SAGE [2] (Soviet - American Gallium Experiment). In these detectors, the isotope Ga-71 is converted to radioactive Ge-71 following the capture of a neutrino. Subsequently, the atoms of Ge-71 thus produced are removed quantitatively from the target solution and counted in a low-level gas-proportional counting detector. The small mass difference of 233 keV between the ground states of the Ga-71 -- Ge-71 isobaric pair makes this neutrino capture reaction the first to be sensitive to the low energy proton-proton (pp) fusion neutrinos resulting from the main energy-producing reactions inside the sun ($E_{pp} < 0.42$ MeV). The other two operating detectors which continue to report a neutrino deficit, Kamiokande in Japan and the historic Davis Chlorine Detector in the United States, are sensitive to the less prominent higher energy neutrinos resulting mainly from the stellar synthesis of B-8 or Be-7; thus the gallium experiments offer the first crucial data to resolve the "solar neutrino problem."

GALLEX achieved the first observation of solar neutrinos attributable to the presence of the proton-proton chain following a period of observation of 295 days in 14 separate solar run exposures which ran from 14 May 1991 to 31 March 1992. These initial GALLEX results were reported in June by Kirsten [3] at the Neutrino '92 Meeting in Granada, Spain. This announcement was immediately followed by the publication of two articles: the first [4] describes the experimental results and the second [5] summarizes the implications of these results. Since then, these 14 runs and one additional run, which extends the exposure coverage to 29 April 1992, have completed counting; they yield an updated result for GALLEX I which is in clear agreement with the first report. A new series of exposures (GALLEX II) has now begun in a further improved experimental configuration.

2. The GALLEX Detector

GALLEX is an international collaboration involving groups from Germany, Italy, France, Israel and the United States. The experiment is located underground in Hall A of the Laboratori Nazionali del Gran Sasso (LNGS), Assergi, Italy which is operated by the Italian National Institute for Nuclear Physics (INFN).

The target material of the detector consists of 30.3 tons of gallium in the form of a gallium chloride - hydrochloric acid solution which, in total, weighs 101 tons. Cross sections for neutrino captures, are, of course, very small so the unit of choice is 1 SNU = 1×10^{-36} captures/ target atom - sec. At a Standard Solar Model predicted capture rate of 132 SNU [6], slightly more than 1 atom of Ge-71 is produced per day. The length of exposure is typically three to four weeks, and during this time some of the Ge-71 atoms decay (11.43 day half-life). To count such a small number of atoms requires their quantitative removal and subsequent introduction into an ultra low-level counting system. Thus, the experiment must be placed underground in order to reduce the unwanted cosmogenic production of Ge-71 from other than neutrino sources and, furthermore, to limit the counter backgrounds.

Basically, the trick to the detector's success in picking out individual Ge-71 atoms hinges on its chemical design. When Ge is produced in the gallium chloride solution (which is high in chloride ion concentration) it forms the volatile gas $GeCl_4$. This gas is purged from the solution by a nitrogen stream which carries the $GeCl_4$ to a series of desorber columns. Here the $GeCl_4$ molecules undergo a reverse reaction; they preferentially dissolve in a counter-flowing water stream (which is low in chloride ion concentration). In the $GaCl_3$ solution, the Ge exists in the IV oxidation state, as in $Ge(IV)Cl_4$ so the removal process involves just a physical desorption, and no additional chemical oxidation step is needed.

Following desorption, the water solution is acidified with gaseous HCl to re-generate the $GeCl_4$ vapors which now leave the solution in the desorber columns. These are then transported and concentrated by dissolution into a smaller volume of water (about one liter). This liter of water is put in a closed funnel containing 500 ml CCl_4, acidified with about two liters of concentrated HCl (to re-form $GeCl_4$) and shook vigorously. The $GeCl_4$ is thus extracted into the CCl_4 phase (Ge and C are similar in the sense that they are members of the same family in the periodic table, thus $GeCl_4$ will dissolve in CCl_4) and finally back-extracted from CCl_4 into 50 ml of tritium-free water. From here on, the procedures use specially developed low-level chemistry and counting techniques. The germanium is chemically reacted with sodium borohydride to produce the counting gas, germane (GeH_4). This gas is purified using gas chromatography. Typically one milligram of non-radioactive germanium carrier with varying ratios of Ge-72, 74 or 76 is added at the start of the exposure, so the final gas volume is typically 0.3 ml at STP and represents an overall tank to counter yield at the ninety percent level. (This increases notably in GALLEX II due to changes in the tank configuration.) Old xenon is added to obtain a counting gas mixture of 30% germane - 70% xenon, with a final gas volume of 1.0 ml. In summary, by exploiting a sequence of chemical equilibria and reactions, the few atoms of Ge-71 in the 101 ton target are transferred into a very small detector for counting.

The counting system, which lies at the heart of this type of experiment, is itself designed of low-level materials and developed with special precautions to shield out background producing effects. The counting techniques exploit energy and pulse-shape analysis to achieve counter backgrounds in the windows of interest at the level of a few counts in a hundred days. The average total 2 FWHM counting efficiency is 65.8 percent. Some of the counters can be placed in a NaI well-detector and used in an anti-coincidence mode to assist in background rejection. The samples are counted for typically 180 days or more to determine the counter backgrounds, and well-studied calibrations of rise time and energy are periodically taken.

3. Data Treatment and Results

The collected data consist of a time sequence of events which are recorded with energy and pulse-shape information. A number of cuts are made on the data in order to eliminate the obvious background events. These are:

(i) elimination of events in coincidence with a NaI veto and thus not attributed to Ge-71 decays;

(ii) elimination of events for four hours following the start of counting (in early runs) to correct for radon daughters on the outside of the counter during handling;

(iii) elimination of events 15 minutes prior to an unvetoed overflow event or three hours after such an overflow to eliminate effects of any radon inside the counter (overflow events can signal alpha

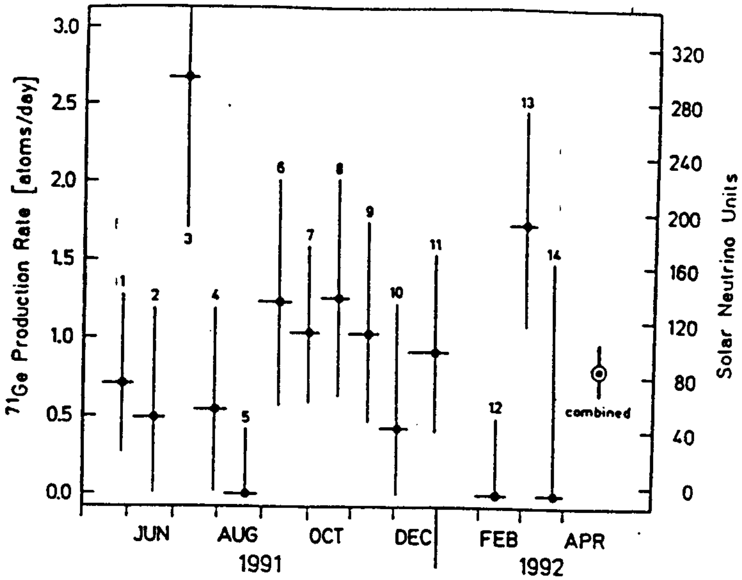

Fig. 1. The GALLEX solar neutrino signal for individual exposures. The results from the first 14 solar neutrino runs are depicted along with their one sigma error bars. The Ge-71 production rate in the tank during a given exposure is indicated on the left and the result in Solar Neutrino Units (SNU) on the right. The right side includes a 6.85 SNU subtraction corresponding to the known contributions which are not due to solar neutrinos.

on solar theories to accommodate a persistent deficit as well as deficits in other solar neutrino experiments.

Solar neutrino oscillations have been suggested for some time to account for the deficit of neutrinos observed by the first Chlorine detector [18,19]. With the theoretical discovery of matter enhanced neutrino oscillations (MSW effect; Mikheyev-Smirnov-Wolfenstein) [20,21] the hypothesis of neutrino oscillations becomes more popular since it readily accounts for large variations of neutrino fluxes with an economical choice of enticing assumptions.

In the MSW mechanism, the neutrinos emitted via the weak interactions are assumed to have masses and these masses differ amongst the different neutrino flavors. They are, however, not in mass eigenstates. The mass differences, denoted by Δm^2 (the difference in squared masses) and values of $\sin^2 2\theta$ (theta is the mixing angle) conveniently parameterize the MSW predictions for solar neutrino fluxes. In the absence of matter, neutrino vacuum oscillations would still occur; in which case, one scenario [22] still remains plausible to account for the observed neutrino deficits: the case of $\Delta m^2 = 10\hat{}(-10)\ eV^2$ with $\sin^2 2\theta$ near unity. [In this solution the oscillation wavelength (1.65 astronomical units) is of the order of the sun -- earth distance.] For the case of the MSW effect, however, the weak interaction between the neutrinos and the solar matter tend to balance the mass differences, consequently two effects are now very important in affecting the magnitudes of the oscillations so that a parameter-space rich in physical interpretation then results. Since flavor changing probabilities are dependent on the neutrino energy, the different solar neutrino experiments (each of which is sensitive to differing solar neutrino energies) see varying suppressions of the intensities of emitted neutrinos across the energy spectrum. The net result is that one can decays in the Rn-222 decay chain; also, events up to three hours prior to a double pulse in a slow transient digitizer which could be attributed to a Bi-Po decay pair in the Rn-222 daughter chain are also eliminated where applicable).

The counting period deadtimes thus introduced are then appropriately taken into account and the cut efficiencies are determined by suitable calibrations.

Having removed these background events, a number of very distinctive indicators of the Ge-71 signal are clearly obtained. These include: (i) groupings of events in the two separate energy -- pulse-shape windows (K peak window and L peak window in the Ge-71 decay), (ii) a characteristic energy spectrum along with a diminishing of the peaks in this energy spectrum in time periods which are multiples of the mean life; and, (iii) a plot of events versus time clearly indicating a decaying component with a half-life consistent with that of Ge-71.

The quantitative result is obtained by use of a maximum likelihood method which is based on the time of appearance of events in the energy -- pulse-shape windows. For the combined runs, the analysis gives a mean production rate of (90 +/- 19) x 10^(-36) Ge-71 atoms per target atom per second prior to corrections for side reactions. The analysis uses a maximum likelihood fit to one overall single production rate together with individual K and L window backgrounds for each counter. The maximum likelihood result is checked by comparison of the fitted parameters to plots of the actual data. Amongst numerous other checks not summarized here, a maximum likelihood fit to the mean life gives 13.5 + 5.2 / -3.5 days; a number which is within statistics of the 16.49 day Ge-71 mean life.

Following the subtraction of the known background contributions and the inclusion of a background Ge-68 (288 day) correction, the final result is 83 +/- 19 (stat.) +/- 8 (syst.) SNU. This number is to be compared to a benchmark Standard Solar Model prediction of 132 +/- 7 SNU (model dependent). In view of the expected contribution of 71 SNU from pp neutrinos and 132 SNU from all solar neutrino branches, this measured result constitutes the first observation of the neutrinos resulting from the main energy-producing reactions inside the sun.

The counting of all results in GALLEX I was completed at the start of November 1992, and the final results will be presented in the immediate future. They indicate continued agreement with the first analyses. A plot of the results from the first 14 individual runs as of 31 March 1992 is indicated in Fig. 1.

Tests of the GALLEX result are on-going. Also, progress continues on the preparation of a neutrino source in the mega-Curie range to test operation of the detector. This source is based on the use of neutron-irradiated chromium enriched to 40% in Cr-50.

4. Implications for Neutrino Physics

The GALLEX result, to be refined over the next few years, is of important interest to neutrino physics. A number of explanations theoretically advanced to account for the solar neutrino deficits include neutrino decay [7,8,9], a time variation of the neutrino flux [10-14] (possibly including magnetic moment interactions) or neutrino masses and oscillations [15]. The last case certainly receives much current attention. Although the measured rate of 0.63 of the predicted solar neutrino value by GALLEX is still within about two sigma of the solar model results [16,17], severe constraints may result delineate regions of the Δm^2 versus $\sin^2 2\theta$ parameter space which are compatible with the results of the solar neutrino experiments and thus constrain the neutrino properties.

Using the first results from GALLEX, the Chlorine experiment and the Kamiokande experiment, the relevant MSW regions are depicted in Fig. 2 as taken from [5]. To construct this figure, the three experiments are fitted using a chi-squared method to the three results predicted by the two neutrino version of the MSW theory (for each of the three experiments) in the Δm^2 -- $\sin^2 2\theta$ parameter space. Two regions result at the 90% confidence level as indicated in the figure. They predict "small" or "large" mixing angles with neutrino masses in the range well below the eV levels characteristic of limits on neutrino masses set by experiments using low-energy nuclear transitions. The two small regions which are obtained are:

(i) smaller angle region; Δm^2 = 6x10^(-6) eV^2 and $\sin^2 2\theta$ = 0.007

(ii) larger angle region; Δm^2 = 8x10^(-6) eV^2 and $\sin^2 2\theta$ = 0.6

The GALLEX result also excludes certain regions of the MSW parameter space as indicated by the solid line (this exclusion is essentially independent of solar model). The Kamiokande Collaboration [23] excludes the region indicated by the dotted line because they do not see a time variation of the flux due to the earth's rotation (day-night effect).

When the MSW arguments are extended to three neutrino flavors more complicated scenarios can result. In a recent argument, Wolfenstein [24] proposes the possibility for a scheme based on three neutrino oscillations where the neutrino masses scale proportionally to the quark masses. Here a tau neutrino of mass 10^(-2) eV and admixture of $\sin^2 2\theta_{e\tau}$ = 3x10^(-4)

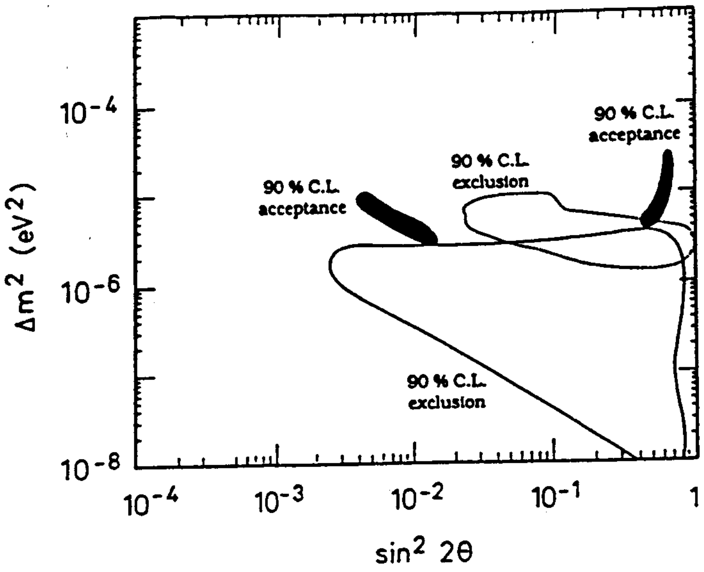

Fig. 2. The MSW parameter space. As described in the text, the GALLEX result constrains the MSW parameters for a two neutrino model to the regions indicated in black. The largest region which is outlined in bold print is excluded by GALLEX. The smaller region which is outlined using dotted print is excluded by the Kamiokande experiment.

suppresses the higher B-8 flux to account for the Kamiokande result and part of the Chlorine reduction (about 3-4 SNU). The remaining reduction of about 1-2 SNU in the Chlorine detector (due mostly to suppression of the lower energy Be-7 neutrinos) is due to oscillations to the muon neutrino which then has a mass in the range of (0.7 - 1.4) x 10^(-4) eV and $\sin^2 2\theta_{e\mu} = 0.2$. This scheme then leads to a gallium prediction of 30 to 70 SNU with the reduction mainly due to conversion of lower energy electron solar neutrinos to muon neutrinos. The GALLEX result at the lower end does not by itself rule out this scenario.

Finally, it is worth noting that the large mixing angle GALLEX solution assuming the two-neutrino MSW model is in a region where a chlorine target could have a large day-night effect whereas such an effect would be most likely undetectable if the small angle GALLEX solution applies.

5. Conclusion

The GALLEX detector sees a clear and positive signal. In the upcoming years, exposures will continue, in order to refine the GALLEX number and reduce the errors. Numerous tests of the detector are planned including an exposure to a man-made source of neutrinos from the decay of Cr-51 at the mega-Curie level.

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References

[1] GALLEX Collaboration: P. Anselmann, W. Hampel, G. Heusser, J. Kiko, T. Kirsten, E. Pernicka, R. Plaga, U. Ronn, M. Sann, C. Schlosser, R. Wink, M. Wojcik (Heidelberg), R. von Ammon, K. H. Ebert, T. Fritsch, K. Hellriegel, E. Henrich, L. Stieglitz, F. Weyrich (Karlsruhe), M. Balata, E. Bellotti, N. Ferrari, H. Lalla, T. Stolarczyk (Gran Sasso), C. Cattadori, O. Cremonesi, E. Fiorini, S. Pezzoni, L. Zanotti (Milano), F. von Feilitzsch, R. Mossbauer, U. Schanda (Munich), G. Berthomieu, E. Schatzman (Nice), I. Carmi, I. Dostrovsky (Rehovot), C. Bacci, P. Belli, R. Bernabei, S. d'Angelo, L. Paoluzi (Roma), S. Charbit, M. Cribier, G. Dupont, L. Gosset, J. Rich, M. Spiro, C. Tao, D. Vignaud (Saclay), R. L. Hahn, F. X. Hartmann, J. K. Rowley, R. W. Stoenner, J. Weneser (Brookhaven).

[2] SAGE Collaboration, A. I. Abazov et al., Phys. Rev. Lett. 67 (1991) 3332.

[3] T. Kirsten, contribution to the Neutrino'92 Conference, Granada, Spain (June 8 - 12, 1992), to be published in the Conference Proceedings.

[4] The GALLEX Collaboration, P. Anselmann et al., Phys. Lett. B285 (1992) 376.

[5] The GALLEX Collaboration, P. Anselmann et al., Phys. Lett. B285 (1992) 390.

[6] J. N. Bahcall, Neutrino Astrophysics (Cambridge University Press, Cambridge: 1989) pp. 344 - 362.

[7] J. N. Bahcall, N. Cabibbo and Y. Yahil, Phys. Rev. Lett. 28 (1972) 316.

[8] J. A. Frieman, H. E. Haber and K. Freese, Phys. Lett. B200 (1988) 115.

[9] Z. G. Berezhiani, G. Fiorentini, M. Moretti and A. Rossi, preprint INFN-FE-05-91.

[10] B. V. Filippone and P. Vogel, Phys. Lett. B246 (1990) 546.

[11] J. N. Bahcall and V. H. Press, Astrophys. J. 370 (1991) 730.

[12] M. B. Voloshin, M. I. Vysotskii and L. B. Okun, Soviet Phys. JETP 64 (1986) 446.

[13] C. S. Lim and W. J. Marciano, Phys. Rev. D37 (1988) 1368.

[14] E. Kh. Akhmedov, Phys. Lett. B213 (1988) 64.

[15] For a review, see for example T. K. Kuo and J. Pantaleone, Rev. Mod. Phys. 61 (1989) 937.

[16] J. N. Bahcall and R. K. Ulrich, Rev. Mod. Phys. 60 (1988) 297.

[17] J. N. Bahcall and M. H. Pinsonneault, Rev. Mod. Phys. 64 (1992) 885.

[18] B. Pontecorvo, Sov. Phys. JETP 26 (1968) 894.

[19] V. Gribov and B. Pontecorvo, Phys. Lett. 28B (1969) 493.

[20] S. P. Mikheyev and A. Yu. Smirnov, Nuovo Cimento 9C (1986) 17.

[21] L. Wolfenstein, Phys. Rev. D17 (1978) 2369.

[22] V. Barger, R. J. N. Phillips and K. Whisnant, Phys. Rev. Letts. 65 (1990) 3084.

[23] K. S. Hirata et al., Phys. Rev. Letts. 66 (1991) 9.

[24] L. Wolfenstein, Phys. Rev. D45 (1992) R4365.