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Update of GALLEX solar neutrino results and implications

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Abstract. The galliumchloride detector operated by the GALLEX-collaboration in the Gran Sasso Underground Laboratory responds primarily to pp-neutrinos. They are produced in the primary fusion reaction of hydrogen into deuterium and directly coupled to the solar luminosity. Standard Solar Models predict ca. 58% of the total signal expected in GALLEX (123-132 SNU [1,2]) to be due to pp-neutrinos. The relative pp-neutrino dominance becomes even larger if the deficit of higher energy neutrinos (as observed in the Homestake- and Kamiokande experiments) is considered.

During the first data taking period (GALLEX I), 15 solar runs had been performed within the exposure period 14.5.1991 - 29.4.1992. The result, 81 ± 17 ± 9 SNU [3] provided the first experimental evidence for pp-neutrinos from the Sun. At the same time, it confirmed the depression of higher energy neutrino fluxes relative to the model predictions. Here we report the results of 15 more solar neutrino runs (GALLEX II), covering the period 19.8.92 - 13.10.93. We obtain 78 ± 13 ± 5 SNU [4]. Evaluated together, the result for all 30 runs is 79 ± 10 ± 6 SNU [4]. While the SNU rate of GALLEX I is well reproduced, the statistical error has been reduced so substantially that a value of signal $+2\sigma$ is required to accommodate not only pp-and pep- but also the ^7Be-neutrino induced ^{71}Ge-production. Contrary, the fate of ^8B-neutrinos has only little discernible effect on the GALLEX data. In conclusion, with the present errors GALLEX constitutes a 2.5 σ problem for ^7Be neutrinos within the frame of "astrophysical" solutions. Alternatively, the particle physics solution (MSW-effect) can consistently explain all available solar neutrino results, leading to a most probable mass scale with the muon-neutrino at approximately 3 meV (milli-eV). However, since the GALLEX result allows the presence of pp and pep neutrinos at full strength, the latter explanation of the data is not forced.

We also give a preview on the upcoming ^{51}Cr source experiment where the gallium target is irradiated with a high flux of low energy neutrinos. ,

1.INTRODUCTION

The neutrinos produced in the solar interior allow a unique real time look into the stellar center and provide a test of the theory of stellar structure and evolution. In the Standard Solar Model (SSM)[5], the neutrino spectrum $N_\nu(E)dE = f(T(r); \rho(r); X,Y,Z(r); t)$ reflects uniquely the present stage of stellar evolution where T(r) and $\rho(r)$ are the radial temperature and density distributions and X,Y,Z are the chemical abundances. All these quantities follow from the mass, the age, t, and the initial chemical abundances X_0,Y_0,Z_0 of the Sun. Energy production is assumed to be ultimately due to fusion of hydrogen into helium. To describe the energy balance, the nuclear cross sections (S-factors) and the opacities are also entering the solar model. It predicts now, for the 4.6 b.y. old Sun, a central temperature of 15.6 million centigrade. Under these conditions, it turns out that the pp-cycle dominates the energy production in the Sun. The expected neutrino fluxes arriving on earth are: 60 billion/cm^2,s from the reaction $p+p \rightarrow d+e^+ +\nu_e$ ('pp'-neutrinos); 4.6 billion/cm^2,s from the electron capture of ^7Be and (only) 5.1 million/cm^2,s from the positron decay of ^8B. Figure 1 shows the expected solar neutrino spectrum[2]. The origin of ^7Be is from ^3He [from d+p]+^4He; that of ^8B from ^7Be+p. In each cycle: $4H \rightarrow {}^4He + 2e^+ + 2\nu_e$, 26.73 MeV of energy and 2 neutrinos are produced. In the steady state the pp-neutrino flux follows from the solar luminosity. For that part, any measured deficits would have to be related to electron neutrino disappearance on the way from the solar core to the earth. The most favored scenario of this kind is neutrino flavor oscillations in media with high and variable electron density (MSW-effect). For this to apply, at least some neutrino mass eigenstates and flavor mixing angles must be non-zero. Values for these parameters can in principle be deduced if distortions of the predicted solar neutrino fluxes are measured. In contrast to the case for pp-neutrinos, fluxes of the higher energy neutrinos (^7Be and ^8B- neutrinos) depend sensitively on delicate branching ratios such as $^3He+^3He$ vs. $^3He+^4He$ and $^7Be + e^-$ vs. ^7Be+p. These in turn depend on details of the solar structure and are much harder to predict. In this case, a measured deficit could either be due to reasons of astrophysics , nuclear physics, or

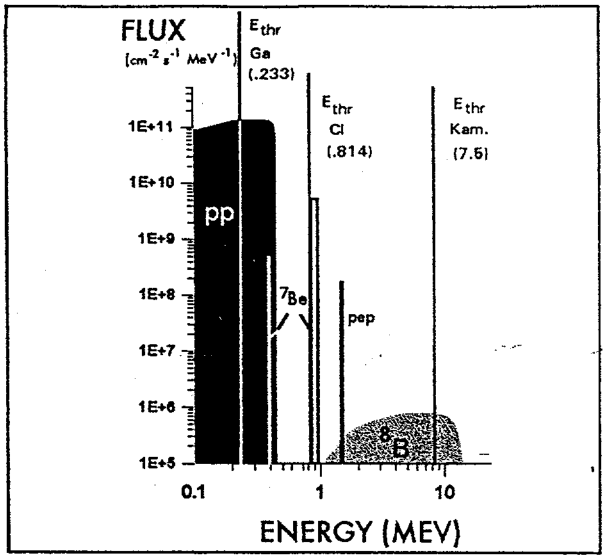

Figure 1. Solar neutrino energy spectrum expected from the SSM. Also shown are the energy thresholds for the gallium, chlorine, and Kamiokande solar neutrino detectors. [The shading code applies also to Figure 2 (→)]
black = pp (and pep) - ν ; white lines = ^{7}Be - ν
gray = ^{8}B - ν ;

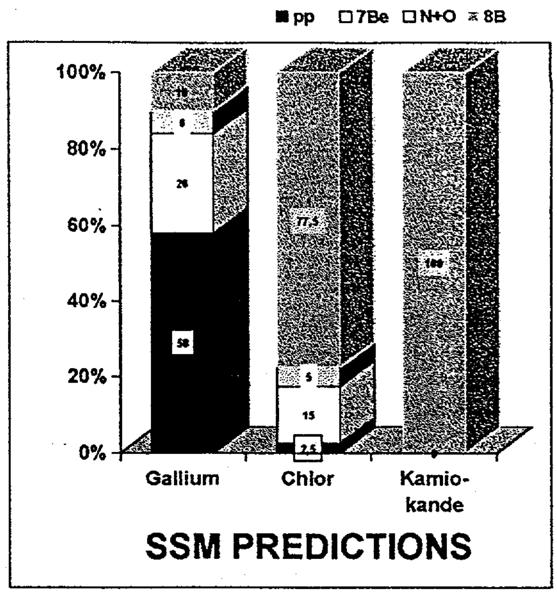

Figure 2. Percentage contributions from the various solar neutrino sources to the signals expected in the presently operating solar neutrino experiments (mean of [1] and [2]). Shading code as in Figure 1.

particle physics. Figure 2 depicts the spectral response of the detectors for which experimental results are available. Only gallium responds to pp-neutrinos (see also the respective energy thresholds in Figure 1).

2. THE GALLEX EXPERIMENT

The GALLEX collaboration [3,4] aims at pp-neutrino detection. To this end for many years to come the only realistic possibility is to use the ^{71}Ga-^{71}Ge scheme in a radiochemical experiment. GALLEX uses 30 tons of Ga in 101 tons of aqueous gallium chloride solution within a single target tank [3]. The SSM- predicted capture rate is comparably high and rather well known: (128 ± 8) SNU (1σ) [1,2]. 58% (74 SNU) are expected from pp (and pep) neutrinos, 26% from ^{7}Be neutrinos and only 10% from ^{8}B (Figure 2). The ^{71}Ge production rate in the GALLEX target is 0.89 atoms per 100 SNU. This translates into ca 12 atoms present at the end of a 4-week exposure period (per 100 SNU). They are extracted as volatile germanium tetrachloride by nitrogen purge together with ca 1 mg of a stable germanium isotope which serves as carrier and allows the chemical yield determination (>98%) in each individual run. Subsequently the $GeCl_4$ is converted into germanium hydride which, after 70% xenon admixture, is a perfect counting gas for proportional counting. For a detailed description of the chemical extraction and preparation techniques see [6]. Big efforts went into the realization of a counting system with unprecedented low background rates. That such backgrounds are crucial can be seen from the fact that, in an individual run, typically only about 5 decay events of ^{71}Ge are observed over a period of about one month. Detected are the Auger electrons and X-rays from the electron capture decay of ^{71}Ge to ^{71}Ga at nominal energies of 10.4 keV (K) and 1.2 keV (L). From the long list of measures and provisions (Table 1) which we have applied in order to achieve the extremely low background rates (order of 1 count per month), here we mention only the pulse shape analysis with a fast transient digitizer for ultimate background discrimination; otherwise we refer to detailed descriptions in [3,7].Counting times are >180 days for each run to characterize the background also after ^{71}Ge decay. A maximum likelihood analysis is then applied to split the measured events into an exponentially decaying signal and a time constant background.

Table 1. Properties and operation environment of GALLEX proportional counters

A: Proportional Counter Optimization

SIZE	miniaturized, 1 mg Ge-carrier, active vol.≈1cc
MATERIALS	ultra-pure: Suprasil, W, Si, zone-refined Fe
SEALING	direct
WALL AND END EFFECTS	shaped cathode
DEAD VOLUME	<5%
COUNTING GAS	30% GeH_4 + 70% Xe; 800 Torr
FIELD STRENGTH	3.6 V/cm, Torr (1600 V)
DRIFT VELOCITY	6 cm/μs
ENERGY RESOLUTION	20% (K); 41% (L)
^{71}Ge DETECTION EFFICIENCY AFTER ENERGY- AND RISE TIME CUTS	70%
CAPACITY	<1μF, low electronic noise
CALIBRATION (END-)WINDOW	shine into total counter Volume (Xe-excit.).

B: Counter Environment

MULTIPLE PASSIVE SHIELDS	Gran Sasso dolomite, Cu, Pb
ACTIVE SHIELD	NaI-well
STABLE ENVIRONMENT	radon protection; clean power; Faraday cage
COMPLETE PULSE SHAPE ANALYSIS	fast transient digitizer
NUMBER OF COUNTERS	large (>30)
COUNTING POSITIONS	24
COUNTING TIME	6 months each
CALIBRATION	3 lines cerium source, Z-scan
CONTINUOS ON-LINE OBSERVATION	optocoupled access
→ BACKGROUNDS	
integral >0.5 keV:	<1 count/2 days
energy/rise time acceptance windows for ^{71}Ge	L-window <1 count/month K-window < 1 count/ 3 months

3. GALLEX RUN SCHEDULE AND RESULTS

The GALLEX solar measurements began 14 May 1991. Our initial data publication with the announcement of the first ever observation of pp-neutrinos appeared in June 1992 (15 runs, see Table 2. The subsequent data releases were in August 1993 (21 runs [cumulative])[8] and in February 1994 (30 runs,[4]). Since our first data release, the major result remains stable while its errors decreased in a consistent manner (Table 2 and Figure 3). In altogether 30 runs so far, 148 ^{71}Ge atoms were seen to decay. Side reactions producing ^{71}Ge in the target are well studied by us, only 12 of the 148 events are due to them (residual cosmic ray muons, fast neutrons, radon and others [3,8]). The results of the individual runs are consistent with statistical fluctuations, multiple consistency checks are applied to the data and confirmed by Monte Carlo simulations.

In Table 2, we also list the results obtained for the K- and L-windows separately. We recall that the apparent asymmetry in the ratio of L and K SNU-values from GALLEX I was shown to be fully compatible with statistical expectations [3]. Nevertheless, it is reassuring to note that with twice as much data available now from GALLEX I+II, this asymmetry has disappeared; the ratio of L and K SNU-values is close to 1.

Because the SNU-values are measured at different times of the year, they inherently include the effect of the variation in the Sun-Earth distance. The semiannual mean for the production rate during the period October-March must be 4% above that for the period April-September, with monthly changes of order 1%. However, if we consider this variation over a full one-year period, its effect on the mean is negligible; thus the individual values in Table 2 have not been corrected for this effect. The results of a separate data analysis for October-March and for April-September are included in Table 2, illustrating that effects of this magnitude are not resolvable.

After each solar run, an instrumental 'blank run' is performed. It copies the solar runs in all aspects except that the exposure time is kept as close to zero as possible. This checks for instrumental artifacts as opposed to time related production processes. The combined result of all blank runs is (-1 ± 7)SNU [4,9], contrasted by the result of all solar runs. For the original data and for details of the data and error analysis, see [3,4,8,9,15]; here we only quote the overall result for our further discussion:

$(79 \pm 10(\text{stat.}) \pm 6(\text{syst.}))$ SNU (1σ) [4].

GALLEX solar neutrino runs continue, with a scheduled interruption from July through October 1994. During this period, a manmade ^{51}Cr neutrino source is inserted into the GALLEX tank to produce

Table 2. Results from GALLEX solar exposure periods. Period GALLEX II is ongoing. Its status is shown for exposures through 13 October 1993, with counting through 4 January 1994. Errors quoted are 1σ.

	GALLEX I	GALLEX II	combined
time period	14.5.91-29.4.92	19.8.92-13.10.93	14.5.91-13.10.93
exposure days	324	406	730
runs	15	15	30
L-result, [SNU]	105 ± 28	66 ± 19	80 ± 16
K-result,[SNU]	64 ± 21	87 ± 17	78 ± 13
(L+K) main result [SNU]	81 ± 17 ± 9	78 ± 13 ± 5	79 ± 10 ± 6
October-March			82 ± 15
April - Sept.			78 ± 14

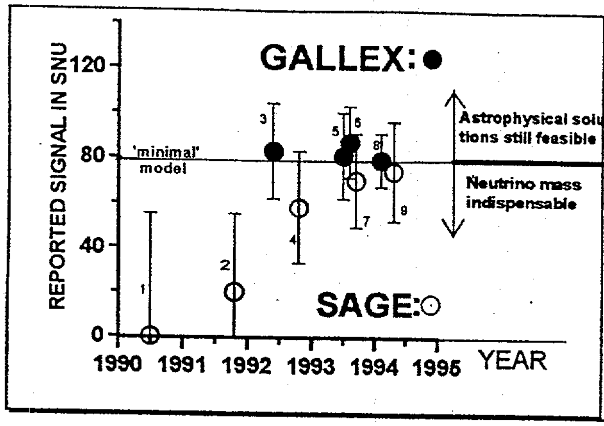

Figure 3. Chronology of GALLEX and SAGE results. The labeled points have been reported in conference proceedings and in open-literature publications. Errors shown are statistical and systematical errors added quadratically. For comparison, the predictions of the SSM cover the range (128 ± 8) SNU (1σ) [1,2]. The horizontal line is drawn at 78-80 SNU, which is the value for a 'minimal' solar model, in which the *total* luminosity is (artificially) assigned to the PPI chain. In the Figure, label 1 = [10], 2 = [11], 3 = [3], 4 = [12], 5 = [8](GALLEX I), 6 = [8], 7 = [13], 8 = [4], 9 = [14]

(initially) 15 times as much ^{71}Ge as the Sun (see section 5). This serves to demonstrate the reliability of the experiment in the concerted interplay of all its components and to exclude any unidentified systematical errors. Not only GALLEX but the credibility of all radiochemical rare event detection methods will be tested and - eventually - demonstrated.

Another gallium-germanium experiment is carried out by the Russian-American SAGE collaboration in the INR underground laboratory in Baksan, Caucasus. SAGE was the first in announcing data in 1990 [10], when they reported a zero signal and reflected on the dramatic consequence for a non-zero neutrino restmass. However, this result did not stand up (Figure 3). GALLEX announced its first result, (83±19(stat.)±8(syst.)) SNU (1σ) in May 1992 [3], allowing the full presence of the pp-neutrinos expected from the solar luminosity. As shown in Figure 3 the SAGE results have meanwhile approached the GALLEX level and the results are now in good agreement:

(74 ± 19(stat.) ± 10(syst.)) SNU (1σ) (SAGE) [14]. In the following discussion we use the GALLEX result, (79 ± 10(stat.) ± 6(syst.)) SNU (1σ) [4].

4. INTERPRETATIONS

The GALLEX result of (79 ± 12) SNU corresponds to (62±10)% of the SSM expectation or 107% of what is expected for pp and pep neutrinos alone. As mentioned, this constitutes the first experimental observation of hydrogen fusion in the solar interior. This is fundamental for the theory of stellar structure and evolution, it transfers stellar models from the realm of theory into the sphere of observational facts as far as the basics are concerned. At the same time, the deviation from 100% indicates a deficit of higher energy neutrinos from ^{7}Be and ^{8}B, confirming what has been found in the Homestake and Kamiokande experiments (Figure 4). A common fit of all these experimental results would require to reduce the central temperature of the Sun from 15.6 to 14.8 Mio °C, which would conflict with the self consistency of the random conditions of the SSM and with helioseismological evidence [16,17,18]. However, if the systematical errors of the respective experiments were underestimated, the apparent conflict between Homestake (factor of 3 reduction for mainly ^{8}B-neutrinos) and Kamiokande (factor of 2 reduction for ^{8}B neutrinos) could reduce to a ^{8}B-absolute flux problem, and this is recently reconsidered [19] in view of the near impossibility of a reliable and accurate prediction of the tenuous (10^{-4} branch) ^{8}B-neutrino flux (cross sections, in particular for the ^{3}He+^{4}He and the ^{7}Be+^{1}H reactions [20], plasma effects, rotating inner core, mixing,...).

On the other hand, a 'new' solar neutrino problem (= deficit of ^{7}Be- neutrinos; a 15% branch in the Sun) may develop from the gallium data. Taken for themselves they are still compatible with the SSM at the 2.5σ level (Figure 5), but with further statistical error reduction there is a possibility that this becomes a more significant discrepancy. Though statistically less dramatic than the ^{8}B-neutrino deficit, it would be conceptually more serious than the latter. Since the ^{8}B-contribution to the ^{71}Ge production rate is insignificant, one would naturally assign the deficit

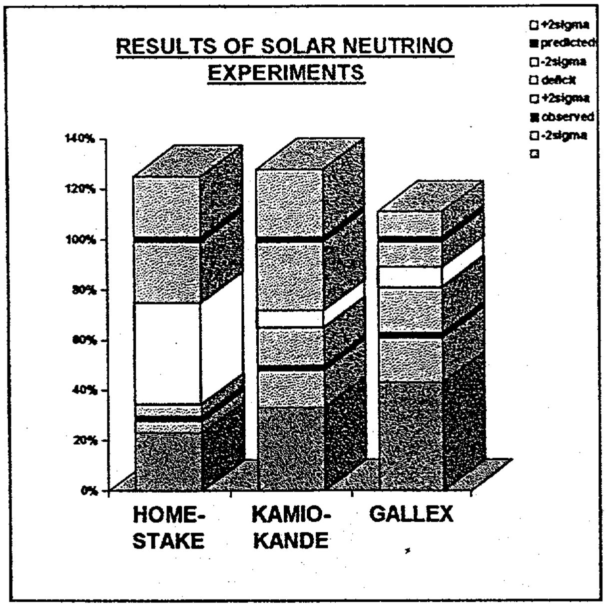

Figure 4. Major results from solar neutrino experiments in percent of the SSM-expectation [1,2] with their respective ±2σ errors. The ±'2σ' uncertainty of the theoretical prediction (set=100%) is also shown. For the spectral sensitivity of the experiments, see Figure 1. Homestake:[23]; Kamiokande: [24]; GALLEX: [4].

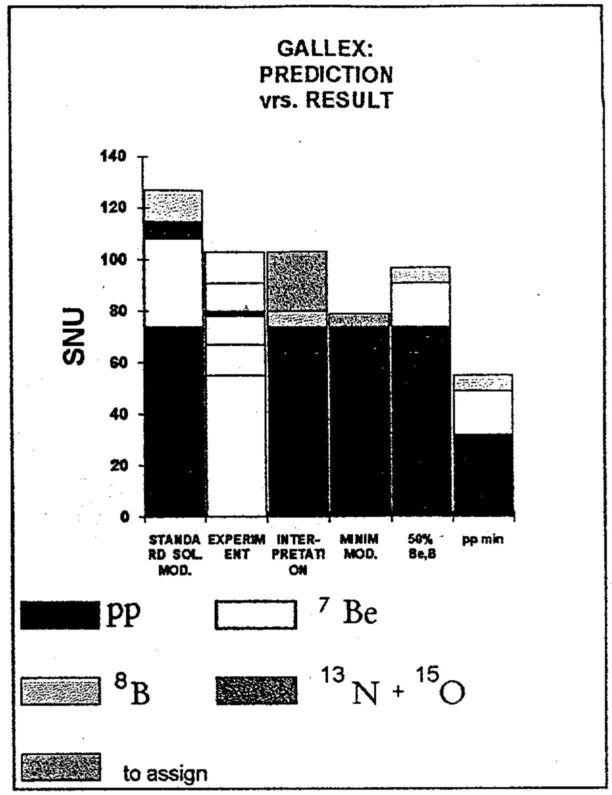

Figure 5. Illustration of various possibilities to partition the measured rate (second column; ± 1σ and ± 2σ) to various solar neutrino branches. If the expected pp-flux is assigned first to the measured signal, then (signal + 2.5σ) is required to accommodate the undepressed expected ^{7}Be-neutrino flux. Other cases shown are: (3.col.): ^{8}B-ν reduced (1/2) as measured by Kamiokande; (4.col.): minimal model, pp(I) only; (5.col.): non-pp neutrinos reduced by factor 2; (6.col.): (signal - 2σ) with non-pp-neutrinos reduced by factor 2.

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to ^{7}Be, the second largest contributor to the gallium signal according to the SSM (26% , Figure 2). Even then, a 'conservative' solution like an eventual revision of the ^{3}He+^{4}He cross sections used in the stellar model calculations is not excluded, but the MSW solution could become more likely. It would then tend to support a muon-neutrino restmass of about 3 milli-electronvolt and a mixing angle near θ = 2° [4,21].

5. THE CHROMIUM SOURCE EXPERIMENT

Well advanced preparations are underway for a straightforward demonstration of the reliability of the GALLEX experiment in particular and of the radiochemical rare event detection technique in general by exposing the Ga target to a calibrated, intense, man-made low-energy neutrino source. We will use neutrinos emitted in the electron capture decay of ^{51}Cr (Figure 6) whereby the latter is produced by neutron activation of ≈36 kg high purity metallic chromium granulate enriched to 38% of ^{50}Cr (natural abundance 4.35%) in the 35 MW SILOE reactor at Grenoble. A 1.7+ MCi source strength is anticipated.

With the source suspended within a reentrance tube inside the gallium target (Figure 7) an initial ^{71}Ge production rate of ≥15 times that measured for the Sun is expected. The exposure will last for ≈ 4 months, until the rate is decreased to ≈ 1 times the solar rate (the ^{51}Cr-half-life is 27.7 d).

During these 4 months, 11 extractions will be performed for an accuracy of ≈ 10%. The ^{51}Cr neutrinos very much resemble ^{7}Be-neutrinos (Figure 6). Apart from the contribution from the ground state the measured rate will also include the 175 and 500 keV excited state transitions and thus provide a check on these cross sections. The main aim, however, is the exclusion of any systematical errors in the radiochemical detection technique (e.g., unspecified withholding mechanisms, hot atom chemistry). Results from the source experiment should be published by end of 1994.

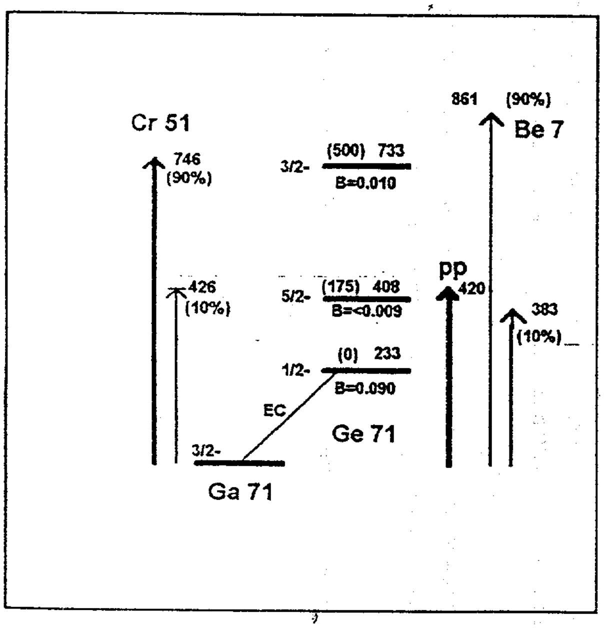

Figure 6. Level scheme for the production of ^{71}Ge from ^{71}Ga through (i)solar pp-neutrinos; (ii) solar ^{7}Be-neutrinos and (iii) man-made ^{51}Cr - neutrinos. Apart from the dominant ground states transition, the 500 keV and 175 keV excited states are inclusive in the ^{51}Cr-source experiment. (Gamov-Teller strengths (B) are from [22]).

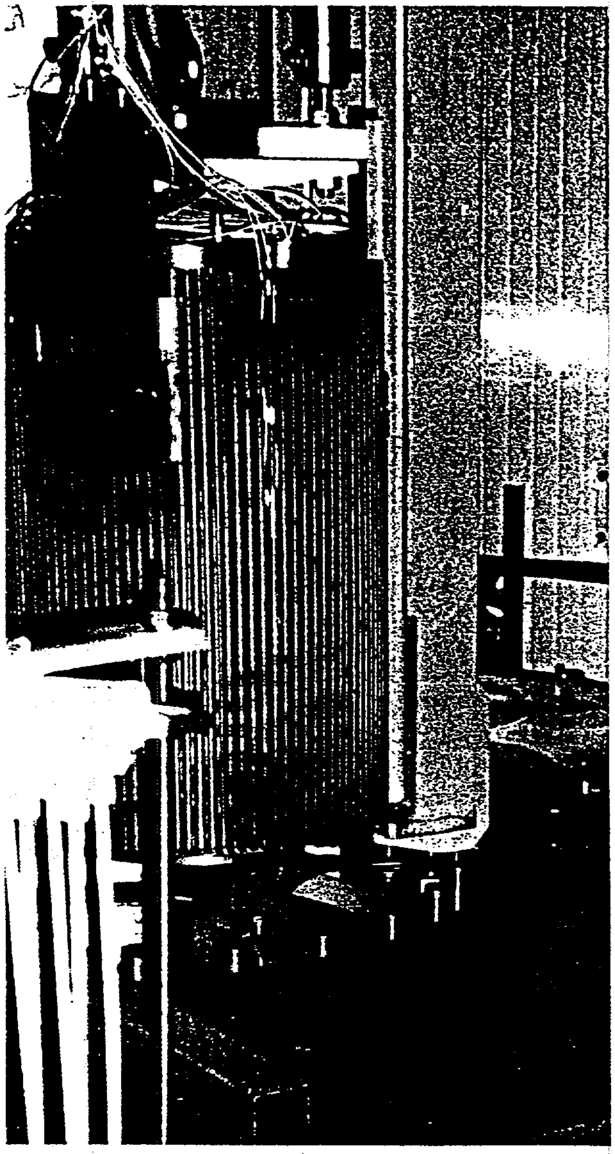

Figure 7. Insertion of the chromium source into the central part of the GALLEX tank.

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