# Toward the ultimate calibration of gallium detector with man-made neutrino source

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**Abstract:** In this note we examine several methods to calibrate in the most efficient way the gallium detectors used in the solar neutrino detection.

We conclude that a gallium target consisting of metallic gallium (detector SAGE) is much more favourable than one based on gallium chloride solution (detector GALLEX). If we make the best use of the existing equipments (GALLEX/ SAGE standard tank, remote handling system, pumping system etc) and enriched chromium (36 kg of chips from GALLEX calibration experiments), we propose 3 variants of definitive calibration experiments to reach a statistical error below 4%: GALLEX standard tank and GALLEX neutrino source but with total activity 5 times more than previous one (≥ 9,6 MCi); SAGE standard tank and SAGE composite compact source but with total activity 5 times more than previous one (≥ 2,5 MCi), and SAGE standard tank with metallic gallium and GALLEX composite source based on chips but with total activity at least 2 times more than previous one (≥ 3,6 MCi).

Other possibilities to carry out new calibration experiments are to use metallic gallium placed into a big vessel containing 50 t of gallium with source based on GALLEX chips (A ≥ 2 MCi or with compact SAGE composite source (A ≥ 1,5 MCi).

As an alternative approach, one could build a compact neutrino source based on $^{37}$Ar isotope with activity of 1,3 MCi (50 t of gallium) or 2 MCi (13 t of gallium).

To irradiate the chromium chips (or rods) we propose to use one of the Russian reactors: the high flux reactor SM-3 (Dimitrovgrad), the fast breeder reactor BN-600 (Zarechny) and the heavy water reactor LUDMILA.

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## Introduction.

The gallium detectors GNO (GALLEX's successor) [1] and SAGE [2] are presently the only observatories continuously monitoring the low energy part of the solar neutrino flux. They measure the principal component of the solar neutrino spectrum thanks to the low threshold of 233 keV for the $^{71}Ga(\nu_e,e^-)^{71}Ge$ reaction, well below the end point of the neutrinos emitted in the proton-proton (pp) fusion. This reaction is predicted by standard solar models to produce 91% of the total flux. Therefore, astronomical inferences and particle physics applications of solar neutrino studies rely strongly on the measured rates in gallium experiments [3]. In the next future, gallium experiments will be a reference for low energy solar neutrino detectors of the "future generation", which hopefully should start in the next decade [4,5].

The measured capture rate by GNO/GALLEX is 70.8 +/- 4.5 (stat.) +/- 3.8 (sys.) SNU[2] [6] with a target of $GaCl_3$ water solution, and by SAGE is 67,2 + 7,2/-7,0 (stat) + 3,5/-3,0 (sys) SNU [7] with a target of gallium metal. These results are both well below the Standard Solar Model prediction from Bahcall et al. [8] of 128 + 9/-7 SNU (measured/expected ratio is 0,55 and 0,53 for GNO and SAGE, respectively). The general implications of these results have been discussed by many authors [2,3,6,9]. We would like to mention that the inferences and applications of gallium experiments will become more stringent as GNO and SAGE reduce the statistical and the systematic uncertainties in the measured gallium rate to reach a global uncertainty < 5%.

The gallium experiments rely on the ability to extract a few atoms of $^{71}Ge$ from several tons of gallium. In such a situation one can legitimately question how well the extraction and counting efficiencies are known. We note that numerous investigations have been undertaken during the GALLEX/GNO and the SAGE experiments to ensure that the various efficiencies are properly evaluated: tracer experiments with stable germanium and with germanium carrier doped with $^{71}Ge$; SAGE experiments in which liquid gallium was spiked with the $\beta^-$ sources $^{70}Ga$ and $^{72}Ga$ which decay to $^{70}Ge$ and $^{72}Ge$; the spiking of the GALLEX detector with $\beta^+$ source $^{71}As$, which decays to $^{71}Ge$ [2,9]. Nevertheless, the most direct experiment of this type involved the irradiation of gallium with a known flux of low energy neutrinos from man-made neutrino source, so-called the source calibration experiments. As the source activity can be measured to very good accuracy (~ 1- 2%), the experiment determines the product of the efficiency and the cross section $\langle\varepsilon\cdot\sigma\rangle_{71Ga}$. Thus any interpretation of the results as a test of

[2] 1 SNU = ($10^{-36}$ interaction/s/target atom)

recovery and counting procedures requires strict bounds on cross section uncertainties. On the contrary, if we believe that the chemistry is well understood due to the experimental tests mentioned above, one can address the question of the neutrino cross section.

The measured neutrino capture cross section $\sigma$ derived from calibration experiment, can be written as:

$$\sigma = (dN/dt) / \varepsilon \cdot A \cdot D \cdot \langle L_\nu \rangle$$

where A is an activity of the neutrino source, $D = \rho \cdot N_o \cdot f/M$ is the atomic density of the target isotope, $\langle L_\nu \rangle$ is the mean path length of neutrino through gallium target and dN/dt is the capture rate of neutrinos in gallium around the source, $\varepsilon$ is the efficiency of recovery and counting procedures.

In the past, both gallium collaborations carried out calibration experiments with neutrino sources based on $^{51}$Cr isotope: GALLEX Collaboration built two neutrino sources with activity of 1,71 MCi and 1,87 MCi respectively [10] and the SAGE Collaboration made a neutrino source with activity of 0.516 MCi [11].

The SAGE Collaboration measured the $^{71}$Ga/$^{51}$Cr cross section value with an accuracy of 12.3% [11]. The combined results of the two GALLEX calibration experiments, the ratio R between activity deduced from $^{71}$Ge counting and the directly measured activity of the source is measured with the accuracy of 8,6 % [10].

The main goal of future calibration experiments is to reduce the statistical and systematic errors up to about 4% each (< 2,8 SNU) [3,12]. In this Note we will discuss only a possibility to reduce the statistical error of the experiment and leave aside the problem of systematic uncertainties.

To improve the statistical uncertainty several possibilities exist :

- increase of the atomic density D, (# at/cm$^3$ ) of the irradiated target.
- increase of the mass of gallium (up to 50 t) which increases the effective path length, $\langle L_\nu \rangle$;
- increase of the detector efficiency (extraction, counting);
- increase activity of the source A;

Obviously, the atomic density D is higher in metallic gallium ($\rho$ = 6,095 g/cm$^3$), $2{,}10 \cdot 10^{22}$ at/cm$^3$ [11] compared to $0{,}1946 \cdot 10^{22}$ at/cm$^3$ for gallium chloride water solution target [13]. Thus, a direct way to improve the accuracy of the $^{71}$Ga neutrino cross section measurement is to carry out the calibration experiment with metallic gallium target (the SAGE detector's case).

The $<L_\nu>$ value rises as the typical size of the gallium target and goes with the mass of gallium as ~ $m^{1/3}$. Thus, the maximum effect of increasing of a mass of gallium from 13 t up to 50 t is only factor $K_{Ga} \sim (50/13)^{1/3} \sim 1.6$.

Taking into account a value of the extraction efficiency (~ 90-95%) and a value of counting efficiency for L- and K-peaks (~ 65%) for both experiments, SAGE and GNO, the only way to improve the detector efficiency is to increase the efficiency of proportional counters. At present, to achieve an efficiency for $^{71}$Ge-decays close to 100%, a cryogenic detector should be used [14]. In this case the maximum effect of increasing the detector efficiency is only factor $K_{PC} \sim (100/65) \sim 1.54$.

We would like to stress that the most effective way to improve the statistical error (≤ 4%) *is to increase at least 5 times the activity of the neutrino source*[3].

In this Note we will mainly discuss this possibility.

Let's discuss *preliminary* possible variants of the final calibration for both targets:

a) the gallium chloride water solution target (detector of GNO Collaboration at LNGS, Italy);
b) the gallium metal target (detector of the SAGE Collaboration at Baksan Neutrino Observatory, Russia).

## 1. K-capture isotopes as neutrino source.

The value of the $^{51}$Cr neutrino cross section on $^{71}$Ga consists of two components (see Fig.1): 1) transition to the ground state with very well determined GT strength and 2) transition to 1$^{st}$ and 2nd excited states with estimated contributions of about 5% to the standard value of the total cross section ((58,1 +2,1/ - 1,6) x $10^{-46}$ cm$^2$ [3]). These weak excited state cross sections are only estimated from (p,n) studies [15] and from ($^3$He,$^3$H) studies [16] that have large experimental errors, 50% and 40%, respectively.

The ideal calibration of gallium with neutrino source would use two neutrino sources with different energies: first one should emit only low energy neutrinos ($E_\nu$ < 408 keV) to calibrate transition to the ground state of $^{71}$Ge, and a second with the enough energy to exite 1$^{st}$ and/or both excited states of $^{71}$Ge (i.e. 733 keV > $E_\nu$ > 408 keV and $E_\nu$ > 733 keV). The comparison of the results of these two experiments gives a possibility to separate the contributions of both excited states and so obtain a more reliable interpretation of solar neutrino data.

[3] Another option is to carry out two calibration experiments with sources of lower activity but which should be sufficient to get the required level of statistical accuracy.

A number of K-capture isotopes of different energies were proposed as man-made neutrino sources for calibrating low threshold solar neutrino detectors: $^{51}$Cr [17,18], $^{37}$Ar [19] and $^{75}$Se [20] (see Table 1).

Table1. Main characteristics of K-capture isotopes proposed as neutrino sources.

| Characteristic | $^{37}$Ar | $^{51}$Cr | $^{75}$Se |
|---|---|---|---|
| $E_\nu$ | 813 keV | 751 keV (90,1%)<br>431 keV (9,9%) | 451 keV (96%)<br>572 keV (1,7 %)<br>… |
| $T_{1/2}$ | 35,5 d | 27,7 d | 119,79 d |
| $E_\gamma$ | $5\cdot10^{-4}$ of $A_o$<br>(internal bremsst.) | 320 keV (9,9%) | 821 keV ($1{,}37\cdot10^{-4}$%)<br>572 keV (0,0356%)<br>400, 6 keV (11,48%) |
| Predicted contribution to the excited states of $^{71}$Ge | ~ 5% | ~ 5% | ~ 3% |
| Production of the isotope/(natural abundance) | $^{40}$Ca(n,α)$^{37}$Ar<br>($^{40}$Ca – 96,97%) | $^{50}$Cr(n,γ)$^{51}$Cr<br>($^{50}$Cr – 4,35%) | $^{74}$Se(n,γ)$^{75}$Se<br>($^{74}$Se – 0,9%) |

**The $^{51}$Cr isotope.** The $^{51}$Cr isotope was proposed by V.Kuzmin [17] and later by R.Raghavan [18].This isotope decays by electron capture with a Q-value of 751 keV and $T_{1/2}$ = 27,7 d to the ground state of $^{51}$V (90,1% branching ratio) and to its first excited state (9,9%), which deexcites to the ground state with emission of a 320 keV γ-ray. The neutrino spectrum consists of four monoenergetic lines of 746 keV (81%), 751 keV (9%), 426 keV (9%) and 431 keV (1%).

$^{51}$Cr isotope is produced by neutron capture on $^{50}$Cr with a sufficiently high cross section for thermal and epithermal neutrons (15,9 and 7,8 b, respectively).

Due to its modest natural abundance (4,35%) in $^{50}$Cr, it is required to enrich it. Besides decreasing the irradiated mass to a value that can be acceptably placed in a reactor, the use of enriched Cr reduces the self-shielding during irradiation and reduces the neutron competition from $^{53}$Cr, whose capture cross section for thermal neutrons is very high.

To carry out the calibration experiments, GALLEX used 36 kg of chromium chips (38% enrichment in $^{50}$Cr) and SAGE ~ 0,8 kg of chromium powder (93% enrichment in $^{50}$Cr).

To produce $^{51}$Cr, the chromium chips of GALLEX have been irradiated with high flux reactor Siloe (France). SAGE transformed ~ 0,5 kg of chromium powder into metallic rods (with size of ∅7 mm x 45 mm) and irradiated it with a fast breeder reactor BN-350 (Kazakhstan). GALLEX Collaboration successively produced two neutrino sources with activity of 1,71 MCi and 1,87 MCi, respectively [12] and the SAGE Collaboration produced neutrino source with activity of 0.516 MCi [13].

**The $^{37}$Ar isotope.** $^{37}$Ar neutrino source was proposed by W.Haxton [19] to calibrate $^{127}$I-$^{127}$Xe radiochemical detector. $^{37}$Ar decays exclusively to the ground state of $^{37}$Cl via electron capture, emitting a mono-energetic neutrino with $E_\nu$ = 813 keV. Thus no energetic nuclear γ rays are produced but only internal bremsstrahlung with a yield $N_\gamma/N_o = 5\cdot10^{-4}$. Neutrinos from $^{37}$Ar decay have energy within several percent of the energy (863 keV) of the dominant $^{7}$Be line. As W.Haxton [19] has emphasized, an experiment carried out with an intense $^{37}$Ar source would therefore provide a valuable additional test of the overall efficiency of gallium detectors in observing the important $^{7}$Be neutrinos. Half-life of $^{37}$Ar is 35 days. Due to this fact a required activity of $^{37}$Ar for final calibration experiment can be 26% less than activity of a source based on $^{51}$Cr (2 MCi instead of 2,5 MCi). In this case the expected uncertainty in cross section from counting statistics is 3,5%.

Two techniques have been proposed to produce $^{37}$Ar: thermal neutron capture on $^{36}$Ar (natural abundance 0,34%) after a preliminary enrichment of $^{36}$Ar up to 90%, and through $^{40}$Ca(n,α)$^{37}$Ar reaction in a flux of fast neutrons. Due to some problems such as a high "burning-up" of $^{37}$Ar being produced by thermal neutrons and the necessity of confining a large amount of argon (~ 8 kg) in the source the first technique seems unrealisable. The second way was considered in details by groups from INR AS of USSR and IPPE, Obninsk [21]. There it was shown that $^{37}$Ar should be obtained by neutron irradiation of the calcium-containing target in the fast breeder reactor BN-350, Shevchenko (now Aktau), Kazakhstan. Maximum total activity of $^{37}$Ar which could be produced with this reactor at the same time is 3,5 MCi (54 irradiation assemblies with metallic Ca filling all cells of 1st raw of the blanket).

Under neutron irradiation of natural calcium, isotopes of argon (mainly $^{37}$Ar) and helium are formed. After irradiation the gaseous phase must be extracted from the target. For example, starting material in form of $Ca_3N_2$ compound can be dissolved directly in water after irradiation and the $^{37}$Ar are swept out of the resulting solution. An obvious advantage of this

method is that the high specific activity (0,1 MCi/g ) of the source of $^{37}$Ar is separated from the target. A mass of 10 g of $^{37}$Ar (6 L of a gas at STP) produces an activity of 1 MCi.

It was also shown in [22] that another fast breeder reactor BN-600, Zarechny, Russia could be used for this purpose: specific activity of $^{37}$Ar produced with this reactor will be in a range from 2,3 up to 5,6 Ci/g of Ca depending on the location of the irradiation assemblies (the 1$^{st}$ raw of the blanket and low (high) enriched zone of reactor' core).

Now a Russian-Japan-USA Collaboration is going to produced 0,5 MCi of $^{37}$Ar with the fast breeder reactor BN-600 [23]. According to the programme about 252 kg of calcium oxide will be placed into 20 irradiation assemblies, the last will be installed into the 1$^{st}$ raw of the blanket.

**The $^{75}$Se isotope.** The $^{75}$Se isotope was proposed by one of us, to calibrate the low threshold detector LENS [24], its application for calibrating gallium detector was discussed later [21]. It decays by electron capture with Q-values of 863 keV to the excited states of $^{75}$As, which deexcites to the ground state with the emission of several γ-rays of different energies. Considering the atomic levels to which transitions occur, the main neutrino energies are 451 keV (85%) and 461 keV (11%). Neutrino lines with higher energy of 572 keV (1,5%), 587 keV (0,62%) and 852 keV (1%) should be also mentioned.

The $^{75}$Se isotope can be produced by neutron capture on $^{74}$Se with a large cross section for thermal and epithermal neutrons (51,8 and 520 b, respectively). The starting material should be enriched in $^{74}$Se and depleted in $^{76}$Se because of the large cross section of the latter isotope (85 b). Fortunately, the enrichment procedure can be carried out by gas centrifugation of volatile $SeF_6$. An optimum value of enrichment of Se in $^{74}$Se is of the order of 90%.

The starting material will be in form of tablets of pressed high –purity Se powder, sealed into the hermetic shell of highly pure Al. The size of the tablets is less than 5-6 mm in order to avoid the self-shielding of $^{74}$Se.

The $^{75}$Se has a number of advantages over the isotope $^{51}$Cr used previously: the half-life is much longer by a factor of 4,3 and the energy of its basic neutrino lines is close to the endpoint of the spectrum of pp-neutrinos. Moreover, it provides the possibility of independently determining the cross section for capture to the $^{71}$Ge ground state, so that the interpretation of the results of solar neutrino measurements with gallium detectors will be substantially refined.

Below we will discuss only two isotopes as a neutrino source: $^{51}$Cr and $^{37}$Ar. All data concerning calibration with $^{51}$Cr are summarized in Table 2.

## 2. Safety transport regulations.

An important boundary condition might affect somehow our studies, it is set by the IAEA regulation for the transport [25] of radioactive materials of important activity. According to this regulation and in case of air transport the maximum activity of $^{51}$Cr radioactive isotope packed into a single transport container of the so called type B is 2.4 MCi (90 PBq) - the equivalent limit is 3.2 MCi (120 PBq) for $^{37}$Ar. Because each package must fulfil a limit of dose rate, a parcel really consists of the radioactive isotope and the appropriate shield. Nothing in the regulations forbids to have several parcels in a single air transport. Hence we are forced to divide the full activity in several parcels (3-4) that we call a composite source. The final assembly of these sub-sources has to be made on site. Careful design has to be made and checked in view of easy and safe assembly of the sub-sources and of the existing hanging system.

IAEA regulations offer a possibility to have a single parcel containing the full activity using a so-called type C container. This type of container has to be built and certified according to these even more severe norms. Actually not a single container of this type has been constructed.

Another problem is the heat released during the transport from irradiated material placed inside tungsten shielding (for example, a heat release is 217,4 W/MCi of $^{51}$Cr activity). In case of air transport the maximum surface temperature is limited to 50 $^{o}$C for type B container and to 85$^{o}$C for type B container under exclusive use [25].

## 3. Calibration of gallium chloride solution with $^{51}$Cr source

Here, we use the 36 kg of enriched chromium from GALLEX Collaboration but with an activity at least 5 times higher (≈ 9,6 MCi instead of 1,7 - 1,9 MCi). To produce this activity one should use the Russian heavy water reactor LUDMILA (expected total activity after irradiation 36 kg of chromium chips with enrichment of 38% is ~ 8-10 MCi, depending on the features of reactor's campaign [26]). Taking into account a distance between Dimitrovgrad (or Ozersk) where the Russian reactors are located and the underground laboratory LNGS, Italy the source should be transported by air. According to the IAEA regulations (see previous paragraph) a source of important activity should be divided into several parcels with activity ≤ 2,4 MCi (the geometries of GALLEX/GNO calibration experiments are shown in Fig.2 and Fig.3). One can see later that there is no big difference of $L_\nu$ value between these geometries (see Table 2).

Another option is to carry two calibration experiments with an activity around 6,8 MCi for each run. This activity is obtained not only with LUDMILA but also with the Russian high flux reactor SM-3 (Dimitrovgrad) [27] and the same 36 kg of chromium chips with enrichment of 38%.

## 4. Calibration of metallic gallium with $^{51}$Cr source.

The calibration experiment with metallic gallium could be realized in two ways, depending on the mass of metallic gallium used in the calibration experiment: 13 t or 50 t (maximum amount of metallic gallium available now in Baksan Neutrino Observatory).

***4.1.*** *Standard gallium tank and standard SAGE chromium source(s).*

The source calibration of SAGE was performed inside a standard tank (volume of 2 $m^3$) containing 13 tons of metallic gallium, with a small zirconium reentrant tube in the middle containing the source (Fig.4). The idea of the first approach is to use the existing infrastructure of the previous SAGE calibration experiment: a tank with 13 t of gallium, the extraction system, the counting system, the calorimeter, the remote handling system, etc, but increase 5 times the activity of the source up to ~ 2.5 MCi. At the same time, one should keep reasonable dimensions of this new source (∅ ≤ 80 mm) to fit into the reentrant tube.

This new source will consist of 4 identical parts with the same dimensions as "old" one (∅ 80 mm x 140 mm) to carry out certification procedure with existing calorimeter and allow the use of the remote handling system (see Fig. 5, the geometry of the SAGE tank from [28]).

To match these requirements it is necessary:

- to use high enriched chromium (~ 90%) in form of metallic rods;
- to reach an average specific activity of $^{51}$Cr of 1000 - 1500 Ci/g (SAGE source had a specific activity equal 1000 Ci/g);

The quantity of highly enriched chromium (~ 90% of $^{50}$Cr) available now is ~ 0,8 kg (most of this chromium is in form of the rods which were irradiated in 1994). There is a possibility to produce in Russia a new batch of high enriched chromium (m ~ 1 500 g) for a reasonable price.

To produce a chromium source with such a specific activity (up to 1500 Ci/g), we can use one of the Russian reactors: the high flux research reactor SM-3 or the fast breeder reactor BN-600 [22].

***4.2.*** *Standard gallium tank and the neutrino source based on GALLEX chromium chips.*

The second approach is to use again the standard SAGE tank with V = 2 $m^3$ but with the GALLEX neutrino source of much higher activity.

Here the size of the source is much bigger compared to SAGE' source, and the geometry is less favourable. The calculated path length of neutrino $<L_v>$ into gallium target for this new geometry (Fig. 6) is 45,7 cm compared to 72,1 cm for the previous standard SAGE case. Note that in this case the amount of gallium used is only 11,9 tons. According to our estimation, to reach required statistical accuracy with such a source, its minimum activity should be not less than 3,6 MCi (see Table 2).

For GALLEX composite source (3 sources with total mass of chips of 24 kg) a path length of neutrino $<L_v>$ into gallium target for this new geometry is 46,2 cm (Fig.7). We assume that the diameter of zirconium reentrant tube for GALLEX composite source here (and for next variants with a bigger tank) is 47 cm, instead of 53,5 cm for a single GALLEX source.

As previously said, the Russian nuclear reactors, suitable to irradiate 24 - 36 kg of chromium chips, are heavy water reactor LUDMILA and high flux research reactor SM-3.

**4.3.** *New large gallium tank.*

The third possibilities considered here is to use a new tank (to be built) to accommodate more metallic gallium and the enriched chromium from GALLEX (or SAGE) with highest activity.

The advantage of this approach is to irradiate the full amount of metallic gallium available (50 t) with the most intense neutrino source possible using the present enriched chromium from GALLEX (SAGE) calibration experiment (note, that the diameter of zirconium reentrant tube for GALLEX composite source here is 47 cm, instead of 53,5 cm for single source).

The path length of neutrino into gallium $<L_v>$ for this big tank with GALLEX $^{51}Cr$ sources is (see also Fig.8 and Table 2):

- 120,4 cm (a single with total mass of chips of 36 kg);
- 94,6 cm (3 sources with total mass of 24 kg);
- 93,1 cm (4 sources with total mass of 36 kg).

If we use SAGE composite source (3 SAGE compact sources into zirconium tube with diameter of 10 cm) the $<L_v>$ value is 120,4 cm (Fig.9).

Table 2. Some possible schemes of definitive calibration of gallium detectors (GNO and SAGE) with $^{51}Cr$ source.

| Detec-tor | Mass of Ga, ton | $A_{max}$, MCi | $<L_v>$, cm | K* | $N_0$ (at $^{71}Ge$/day) | $T_{exp,}$ days ($N_{51Cr} = N_{solar}$) | $N_{tot}$ (at $^{71}Ge$) |
|---|---|---|---|---|---|---|---|
| G N O | 30,3 t | **1 x 1,8 = 1,8 MCi (chips)** | **191,5 cm** | **0,03614** | **12,46** | **120** | **474** |
| | | 1 x 9,6 = 9,6 MCi (chips) | 191,5 cm | 0,03614 | 66,4 | 187 | 2 633 |
| | | 4 x 2,4 = 9,6 MCi (Chips) | 190,8 cm | 0,03614 | 66,2 | 186 | 2 623 |
| S A G E | a) 13 t | **0,516 MCi (rods)** | **72,11 cm** | **0,39** | **14,54** | **160** | **571** |
| | | 4 x 0,625 = 2,5 MCi (rods) | 70,52 cm | 0,39 | 68,8 | 222 | 2 740 |
| | b) 11,9 t | 1x 7,2 = 7,2 MCi (chips) | 45,7 cm | 0,39 | 128,3 cm | 251 | 5 120 |
| | | 3 x 2,4 = 7,2 MCi (chips) | 46,2 cm | 0,39 | 129,7 | 251 | 5 179 |
| | c) 50 t | 1 x 9,6 MCi = 9,6 MCi (chips) | 96,8 cm | 0,39 | 362,4 | 233 | 14 444 |
| | | 3 x 2,4 = 7,2 MCi (rods) | 94,6 cm | 0,39 | 265,6 | 222 | 10 584 |
| | | 4 x 2,4 = 9,6 MCi (chips) | 93,1 cm | 0,39 | 348,6 | 233 | 13 903 |
| | | 3 x 0,5 = 1,5 MCi (rods) | 120,4 cm | 0,39 | 70,4 | 169 | 2 773 |

*$A_{max}$ is the maximum available activity of the source for given variant, $<L_n>$ is the effective path length of neutrinos into gallium, $N_0$ is the $^{71}$Ge production rate at the beginning of the exposure, $T_{exp}$ is length of the exposure (the end of exposure when daily production rate from chromium source equals the one from solar neutrino, $N_{51Cr} = N_{solar}$), $N_{tot}$ is total number of $^{71}$Ge atoms produced into gallium (we are not taking into account decay of $^{71}$Ge), $K^* = s \times n \times B_1(Bq/Ci) \times B_2(sec/day)$is the factor of merit ($s = 5{,}81 \times 10^{-45}$ cm$^2$ is a value of cross section of $^{51}$Cr neutrino, **n** is density of $^{71}$Ga atoms ($0{,}1946 \times 10^{22}$ and $2{,}1 \times 10^{22}$ for GNO and SAGE target correspondently), $\mathbf{B_1} = 3{,}7 \times 10^{16}$ Bq/Ci and $\mathbf{B_2} = 8{,}64 \times 10^4$ sec/day).*

*The two lines in bold present the data concerning completed GALLEX and SAGE calibration experiments [10, 11].*

## 5. Ultimate calibration of gallium detector with $^{37}$Ar neutrino source.

*Calibration experiment: standard gallium tank and compact source (SAGE type).*

A calibration experiment with $^{37}$Ar could reuse the infrastructure of the previous SAGE calibration experiment: the tank with 13 t of gallium, the extraction system, the counting system, the calorimeter, the remote handling system for LANL, etc, but increase the activity of the source about 4 times, up to ~ 2 MCi. According to [25], the maximum activity of $^{37}$Ar radioactive isotope packed into a single transport container is 3,24 MCi. Thus the argon source doesn't need to be divided. One should keep reasonable dimension of this new source (a diameter ≤ 80 mm) because of the dimension of the zirconium tube inserted into gallium, whose diameter is 90 mm (Fig 4). It will be useful if this new source would have overall dimensions, which are the same as the dimensions of "old SAGE" one (∅ 80 mm x 140 mm) to carry out certification procedure using existing calorimeter and remote handling system, which may imply to pack the gas at 8-9 bars.

We would like to note that this gaseous source could be certified easily, only taking a small sample of gas, dilute it, and counting it into proportional counter. As a crosscheck of the certification procedure we propose a calorimetric measurement of the whole source with existing calorimeter (heat release of $^{37}$Ar is about 13 W/MCi, bremsstruhlung included).

As we mentioned above, $^{37}$Ar source with activity of about 2 MCi could be used with SAGE standard tank (13 tons of metallic gallium).

## Conclusion.

In this note we examined several methods to calibrate in the most efficient way the gallium detectors used in the solar neutrino detection.

First of all, from data in Table 2 we conclude that a gallium target in form of metallic gallium is much more favourable than one based on gallium chloride solution (the coefficient K* is nearly 11 times bigger).

If we make the best use of the existing equipments (GALLEX / SAGE standard tank, handling remote system, pumping system etc) and enriched chromium (36 kg of chips from GALLEX calibration experiments), we have 3 variants of definitive calibration experiments to reach the statistical error below 4%:

1. GALLEX standard tank with 30,3 t of gallium solution and GALLEX single source but with a total activity 5 times more than the previous one (≥ 9,6 MCi)[4].
2. SAGE standard tank (~ 13 t of metallic gallium) and SAGE composite compact source but with a total activity 5 times more than the previous one (≥ 2,5 MCi).
3. SAGE standard tank with metallic gallium and GALLEX composite source based on chips but with a total activity at least 2 times more than the previous one (≥ 3,6 MCi).

Other possibilities to carry out new calibration experiments are:

1. use a gallium target in form of metallic gallium placed into a big vessel containing 50 t of gallium with source based on GALLEX chips with activity A ≥ 2 MCi or with compact SAGE composite source with an activity A ≥ 1,5 MCi;
2. as an alternative approach, one could build a compact neutrino source based on $^{37}$Ar isotope with an activity of 1,3 MCi (50 t of gallium) or 2 MCi (13 t of gallium).

The $^{51}$Cr source should be fabricated:

- in form of metallic rods with high specific activity (~ 1500 Ci/g, i.e. made from high enriched chromium (≥ 90% of $^{50}$Cr), irradiated with high flux of neutron $\varphi \geq 10^{15}$ cm$^{-2}$s$^{-1}$);
- in form of chips with a specific activity around 300 Ci/g.

To irradiate the chromium rods we propose to use the high flux reactor SM-3 (Dimitrovgrad) or the fast breeder reactor BN-600 (Zarechny). To irradiate chromium chips we propose to use the Russian heavy water reactor LUDMILA or the high flux reactor SM-3. According to regulations for air transport [25], the maximum activity of $^{51}$Cr radioactive isotope packed into single transport container is 2,4 MCi. Thus the neutrino source of important activity should be divided into several separated parcels. The final assembly of these sub-sources will be made on site.

[4] Another option is to carry out two calibration experiments with GALLEX standard tank and GALLEX single source but with an activity of 6,8 MCi for each one.

To produce $^{37}$Ar isotope of such an activity one should use fast breeder reactor BN-600. The $^{37}$Ar isotope source should be fabricated as liquid argon under liquid nitrogen temperature or gaseous argon under high pressure (p ~ 20 atm).

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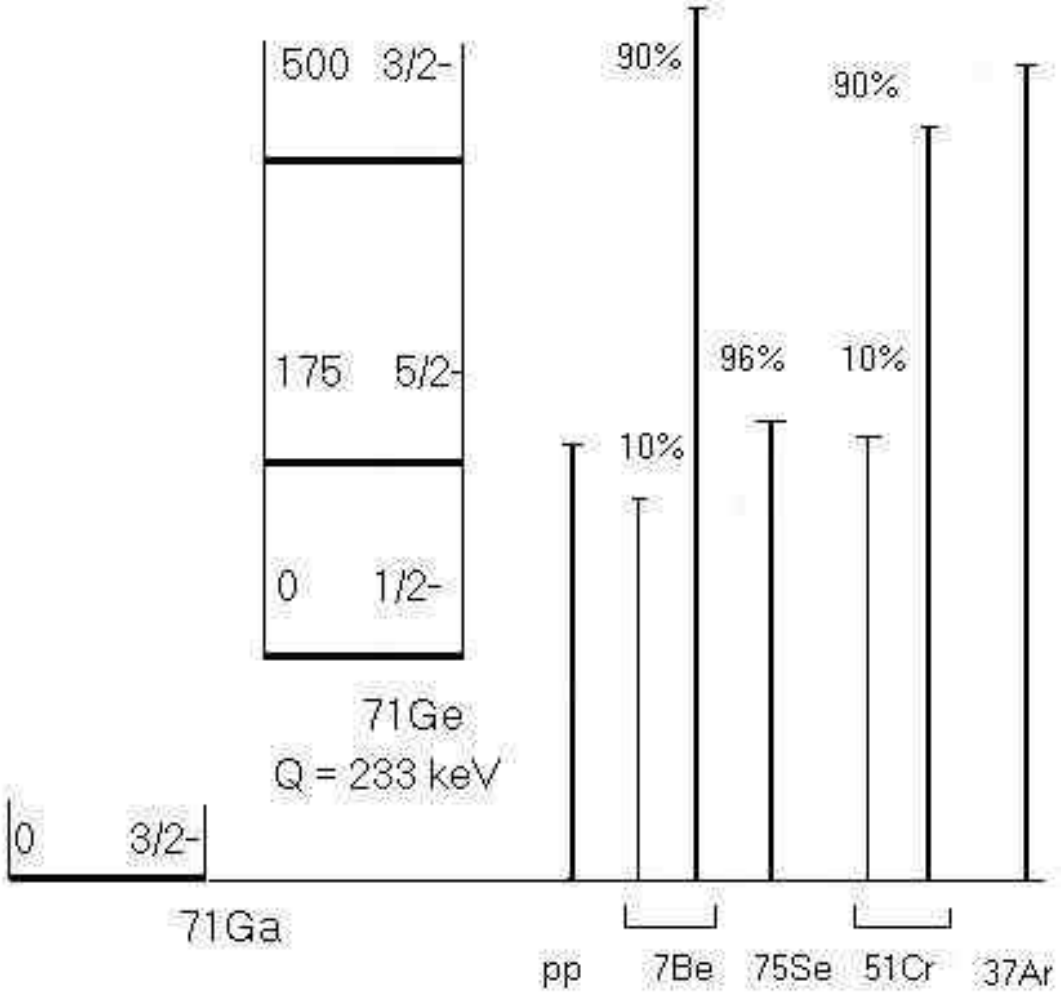



Fig.1. Level scheme for 71Ge showing the excited states that contribute to absorption of pp, 7Be, 75Se, 51Cr and 37Ar neutrinos.

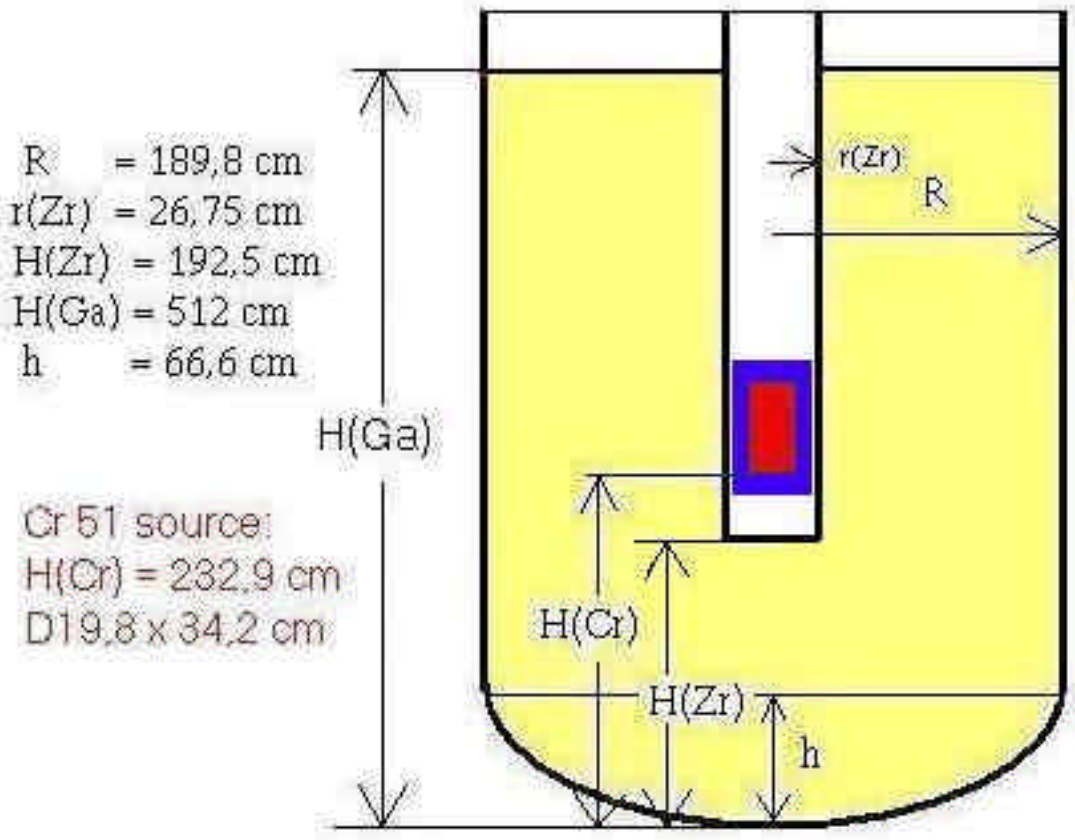



Fig.2. Geometry of GALLEX calibration experiment(s).

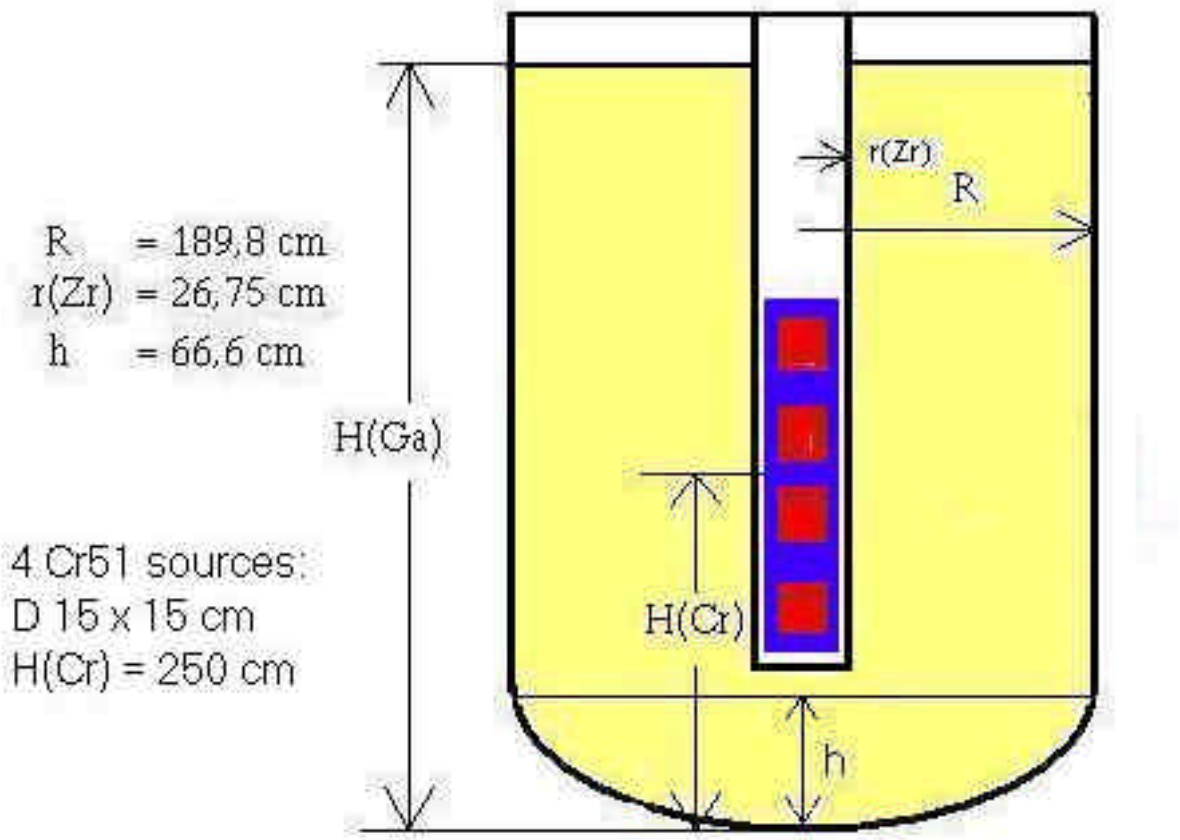



Fig.3. Geometry of new GALLEX calibration experiment.

R = 70 cm
r(Zr) = 5 cm
h = 30 cm

H(Ga) = 117 cm
Ls = 75 cm
Cr51 source:
D 4 x 9 cm
W-shielding:
d = 1,9 cm
Overall dimensions of stainless steel casing with W shielding:
D 8 x 14 cm

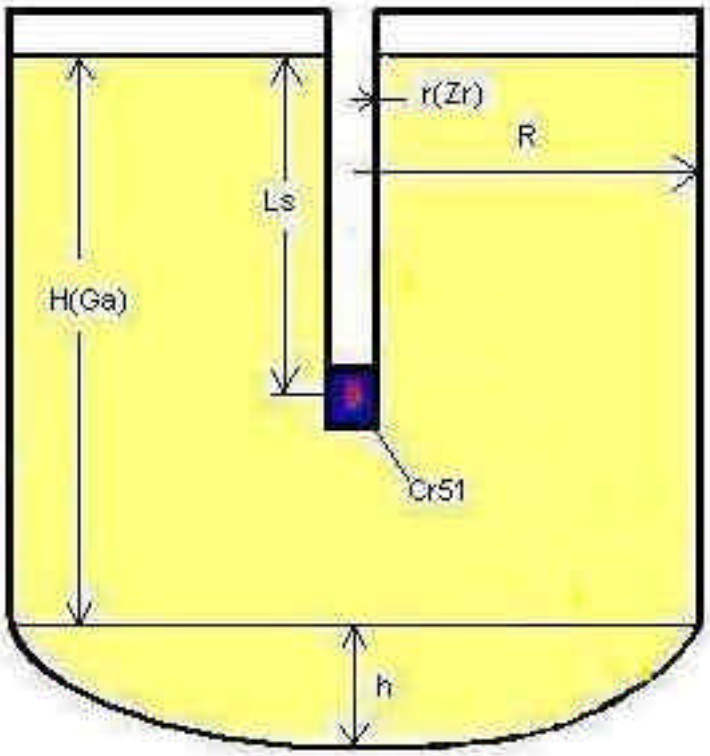



Fig.4. Geometry of SAGE calibration experiment.

R = 70 cm
r(Zr) = 5 cm
h = 30 cm
H(Ga) = 117 cm
Ls = 75 cm

4 Cr51 sources:
D 4 x 9 cm of each

W thickness:
d = 1,9 cm

Overall dimensions of stainless steel casing with W shielding:
D 8 x 56 cm

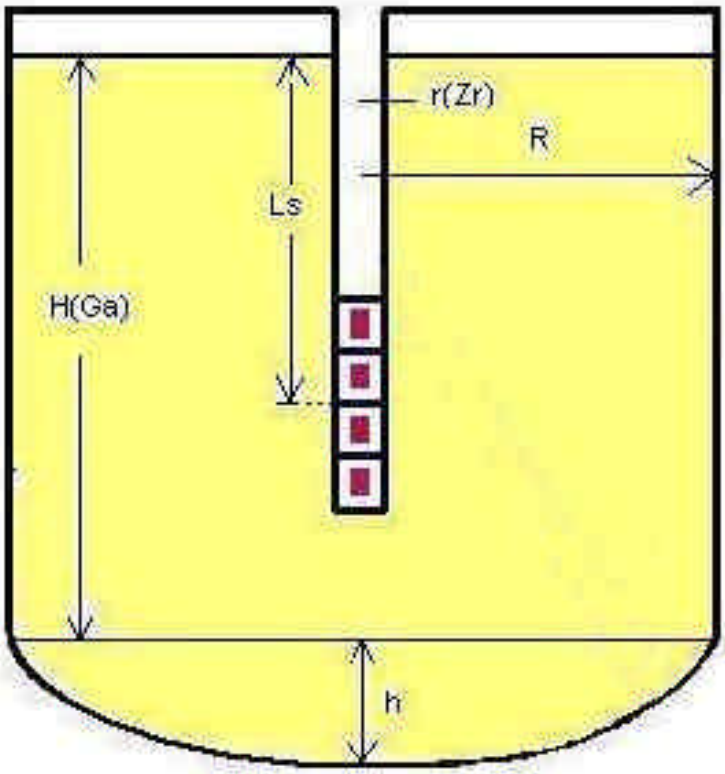



Fig.5. Geometry of new SAGE calibration experiment (with SAGE's composite source).

R = 70 cm
r(Zr) = 26,75 cm
H(Ga) = 117 cm
Ls = 80 cm
L(Zr) = 137 cm

Cr51 source:
D 19,8 x 34,2 cm
W -shielding:
D 38 x 55 cm

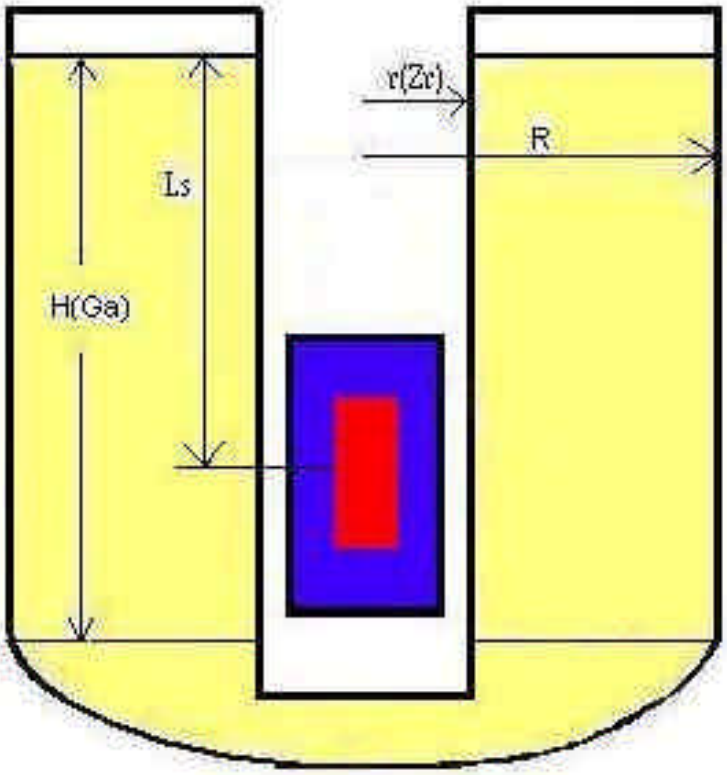



Fig.6. Geometry of new SAGE calibration experiment with single GALLEX source.

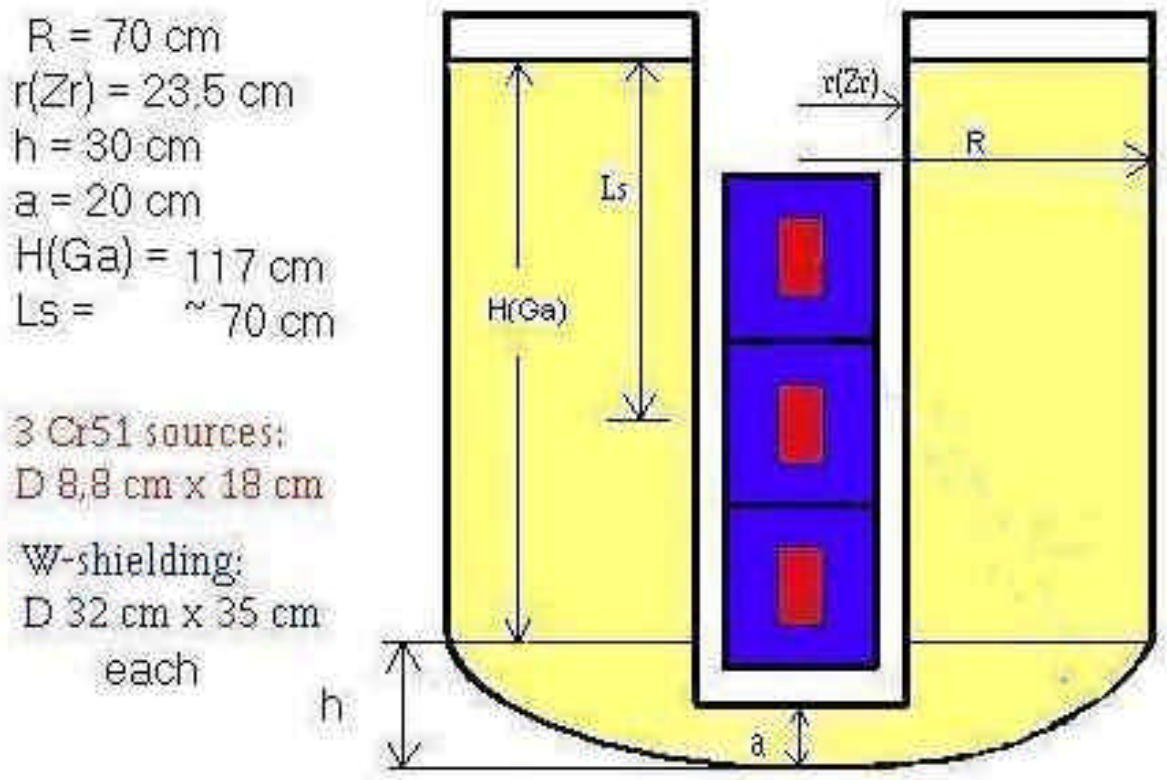
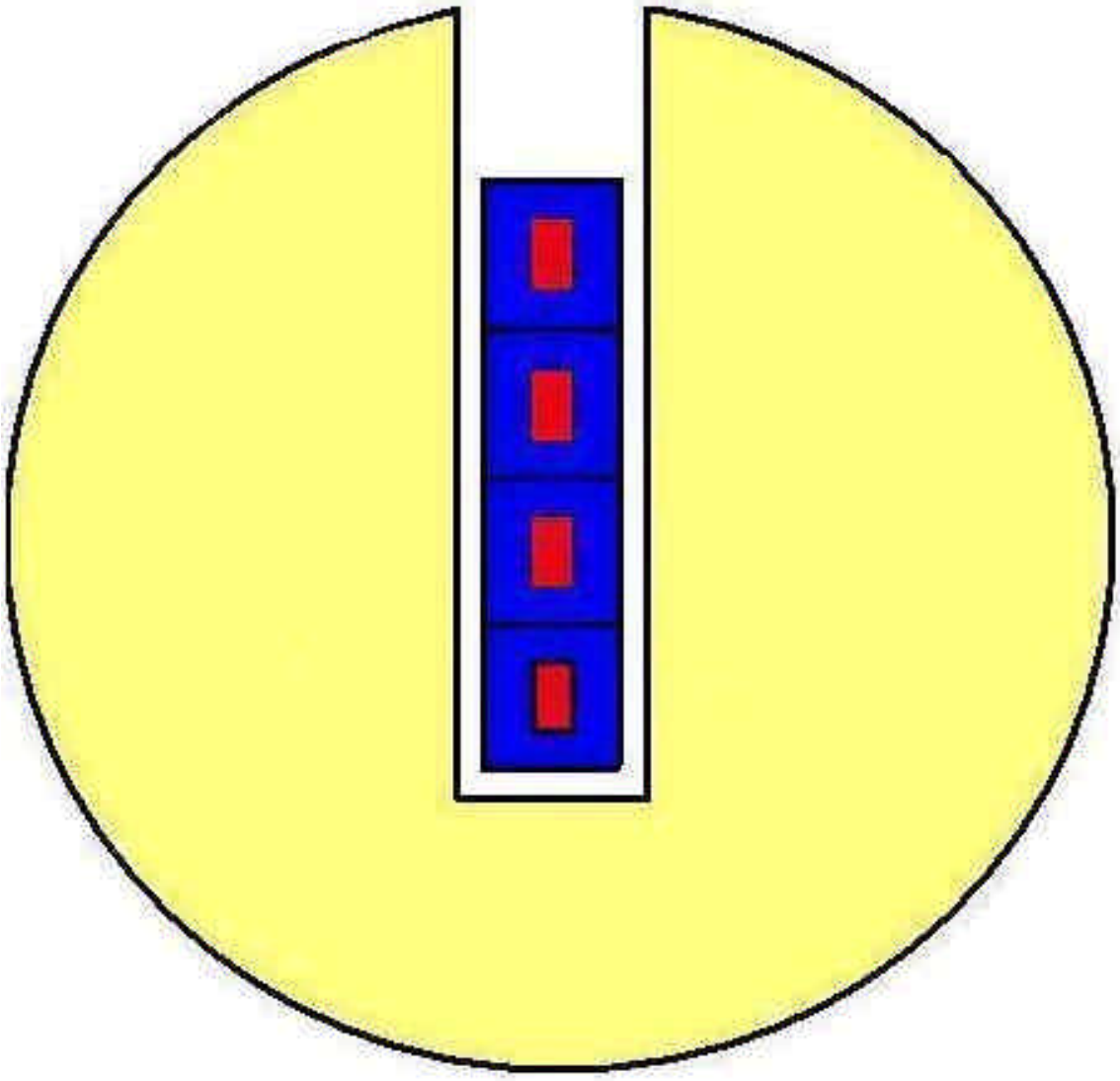


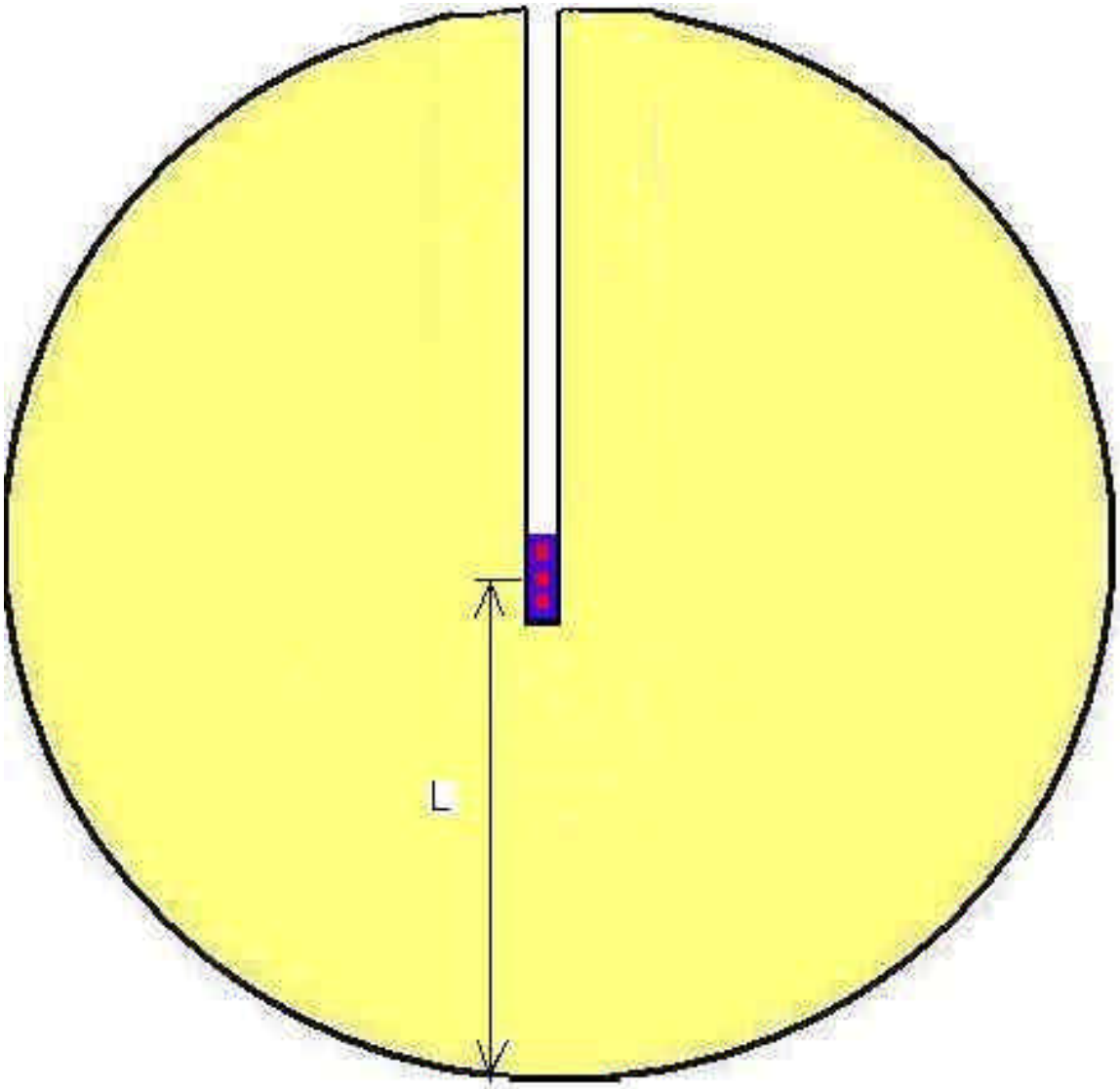

Fig.7. Geometry of new SAGE calibration experiment with composite GALLEX source.



R(Ga) = 128 cm; W-shielding: D 32 x (4 x 35) cm;
Overall dimensions of Zr tube/cooling system: D 47 x 175cm

4 Cr51 sources: 4 x (D 15 x 15 cm)

Fig.8. Geometry of the calibration experiment with 50 t of Ga and GALLEX's composite source.




R(Ga) = 128 cm; Zr tube: D10 x 156 cm;
Three 51Cr sources with W-shielding: D 8 x (3 x 14) cm
L = 125 cm

Fig.9. Geometry of the calibration source with 50 t of Ga and SAGE's composite source (3 compact sources).