CALIBRATION OF SOLAR NEUTRINO DETECTORS WITH ARTIFITIAL NEUTRINO SOURCES BASED ON ^{51}Cr AND ^{75}Se

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Abstract

The possibility of the calibration procedure for the solar neutrino detectors GNO, BOREXINO, and LENS with the same artificial neutrino source have been discussed. Russian heavy water reactor L-2 was demonstrated can be used to produce 10 MCi neutrino source based on ^{51}Cr isotope for this purpose. For the first time have been demonstrated the possibility of production and utilization of neutrino source based on ^{75}Se isotope.

Introduction

Four pioneering experiments - Clorine [1], Kamiokande [2], GALLEX [3] and SAGE [4]- have observed neutrino fluxes with substantially lower intensity than the Standard Solar Model has predicted. This discrepancy constitutes the so-called "Solar Neutrino Problem" (SNP) which is the one of the most intriguing problems of modern physics and astrophysics. Most physicists consider the solution of this problem to lie in new neutrino physics, a possibility of great importance for all of the modern physics.

From the experimental point of view the most important task for solution of the SNP is to continue Ga-Ge experiments for the reason of sufficient accuracy (SAGE [4] and GNO [5]) and to detect of low energy neutrino fluxes from the pp and ^7Be sources with a real time detectors - BOREXINO [6] and LENS [7].

Detector BOREXINO (now under construction in Gran Sasso underground laboratory) is intended to measure of ^7Be-neutrino, as well as to search a neutrino magnetic moment [8] using an artificial neutrino source (ANS).

Detector LENS [7] is based on using a Yb target for the solar neutrino capture. Neutrino capture by ^{176}Yb nucleous results in excited isomer states of ^{176}Lu which decay to the ground state of ^{176}Lu with a time delay of 50 ns. These neutrino events have a highly specific signature two events produced at the same point in the detector with an average delay time. Such a signature gives the possibility of discriminating the neutrino signal against background by a factor of 10^7. The interpretation of such an experiment has one major problem: the neutrino cross-section for the transition of ^{176}Yb to the excited states of ^{176}Lu is known in just order of magnitude (this cross section is deduced from the cross sections of (pn) or $(^3He,^3H)$ scattering reactions on the same isotope [9]). The only possibility to solve this problem is to calibrate the full-scale detector with an ANS of MCi activity.

Artificial neutrino sources based on the isotope ^{51}Cr with an activity of a few MCi have been successfully used for calibration of two gallium detectors, GALLEX [10] and SAGE [11]. For these detectors ANS was mainly used for an overall check on the detector;

for the ^{176}Yb detector the calibration of the detector is necessary in order to measure the unknown cross-section for neutrino capture with an accuracy of not less than 5%.

A scheme for the calibration of three solar neutrino detectors (GNO, LENS, and Borexino) using the same high activity ANS is under development now. Answering questions of principle connected with calibration procedure and creation of ANS with a very high activity for this purpose is the subject of this work.

1. Neutrino experiments with ANS on the base ^{51}Cr and ^{75}Se.

The ^{51}Cr decays by electron capture with a Q- value of 751 keV and $T_{1/2} = 27.7$ days to the ground state of ^{51}V (90.14% branching ratio) and to its first excited state (9.86%), which deexcites to the ground state with the emission of a 320 keV γ-ray. The neutrino spectrum consists of four mono-energetic lines 746 keV (81%), 751 keV (9%), 426 keV (9%) and 431 keV (1%) ([10, 11]).

The ^{75}Se [12] decays by electron capture with Q- value of 865 keV to the excited states of ^{75}As, which deexcite to the ground state with the emittion of several γ-rays of different energy. Taking into account the atomic levels to which transitions can occur, the neutrino energies are 452 keV (83%), 465 keV (11%), 585 keV (2%) and 600 keV (3.5%). The half-life for ^{75}Se is 119.78 days, this allows one to make the calibration experiment quite uninhibitedly.

It is suggested that the neutrino source (the volume of one together with passive shielding is 0.3 m^3) will be placed into a center of the GNO (or LENS) detector (i.e. in full angle geometry). Volume of GNO detector is 54 m^3 [3] and LENS detector is 108 m^3.

Cross section of the inverse beta-decay reaction was calculated according to [13]. Matrix elements for the transitions to the excited states of ^{176}Lu were valued through their Gammov-Teller strength B(GT), which were measured by the (n, p) and $(^3He, t)$ scattering reactions [9].

Fig.1 and 2 show the simplified nuclear data for ^{71}Ge and ^{176}Lu detection of solar neutrino. The Table 1 and 2 list the results of the calculation of neutrino capture events of ^{51}Cr (^{75}Se) neutrinos in GNO and LENS detectors.

To get the accuracy required for GNO detector ($\sim$ 5%), the activity of ^{51}Cr source should be $\geq$ 1.75 MCi and the activity of ^{75}Se $\geq$ 1.77 MCi.

For the experiment with the LENS detector the activity of ANS based on ^{51}Cr should be $\geq$ 4.30 MCi (only events produced by 746 keV neutrinos are analyzed). Taking into account possible problems of the delivery this comparatively short lived isotope from the reactor to the Gran Sasso underground lab, the ^{51}Cr activity should be more than 5.1 MCi.

The required activity of ANS based on ^{75}Se should be more than 3.84 MCi (the events produced by neutrinos with energy of 452 keV and 465 keV are analyzed).

Table 1. Results of calculation of neutrino capture events in the GNO detector. Activity of the ^{51}Cr (^{75}Se) source is 1 MCi. Exposure time is 3 months.

Neutrino source	E, keV	ground state B(GT)=0.0087	175 keV B(GT)=0.05	500 keV B(GT)=0.01	Sum
^{51}Cr	746	205	8.2	5.4	218.6
	426	10.3	0.3	-	10.6
	Sum	215.3	8.5	5.4	229.2
^{75}Se	452	177.7	5.4	-	183.1
	465	24.7	0.7	-	25.4
	585/600	17.4	0.6	-	18.0
	Sum	219.8	6.7	-	226.5

Table 2. Results of calculation of neutrino capture events in the LENS detector. Activity of the ^{51}Cr (^{75}Se) source is 1 MCi. Exposure time is 3 months.

Neutrino source	E, keV	194.5 keV B(GT)=0.21	339 keV B(GT)=0.12	Sum
^{51}Cr	746	72.7	30.7	103.4
	426	4.2	-	4.2
	Sum	76.9	30.7	107.6
^{75}Se	452	70.2	26.8	97.0
	465	9.7	4.0	13.7
	585/600	6.3	2.6	8.9
	Sum	86.2	33.4	119.6

Thus GNO, BOREXINO (and LENS in the future) are placed in the same underground laboratory a chance arose to carry out the calibration procedure all of these detectors using the same ANS of very high activity.

Fig.3(a) shows the schedule of the GNO, LENS and BOREXINO experiments with the same ANS based on ^{51}Cr and the values of ^{51}Cr activity on the different stages of the procedure. The activity of ^{51}Cr at the moment of shut down of the reactor should be more than 8.9 MCi. ^{75}Se can be used as an ANS for GNO and LENS experiments and its activity should be $\geq$ 3.48 MCi (see Fig.3(b)).

For the sake of simplicity we supposed that a time to deliver an ANS from the reactor to the laboratory is 7 days and a time to transfer an ANS from one detector to another is 3 days.

2. ANS production.

2.1. Artificial neutrino source based on ^{51}Cr.

^{51}Cr is produced by neutron captured on ^{50}Cr (a 4.5% natural abundance) with sufficiently high cross section for thermal and epithermal neutrons (15.9 and 7.8 barns accordingly). Source material must be enriched in ^{50}Cr and depleted in ^{53}Cr isotope (because of the high cross section of this isotope equil 18.2 barns) and high contents in the natural mixture (9.5%).

Because of the high cost of enriched chromium was proposed to use already available material, which have been produced before for GALLEX Collaboration (35.6 kg of chromium enriched in ^{50}Cr to 38.6% and depleted in ^{53}Cr (0.7%)).

One more advantage of this material is conclude in that, it is in form of chips and, therefore, it is easy to homogenize ones after irradiation and carry out the sampling procedure. As a result one can determine the activity of the neutrino source by direct methods, and by calorimetry [10]. But it should be noted that there is a need for a big volume ($\sim$ 10 L) in a reactor to place this material because of its low density and certain temperature condition of starting material to avoid a sintering effect of Cr chips.

In Russia there are three reactors, which are suited to produce required activity of ^{51}Cr: fast breeder nuclear reactor BN-600 featuring a special irradiation assembly [14], research reactor SM-3 [15] and heavy water reactor L-2 [16]. The reactor L-2 has a very large volume with high thermal flux neutron (up to $2{\cdot}10^{14}$ cm^{-2}c^{-1}), very effective cooling system and continuous loading/unloading mode for starting material. If ones takes into account a necessity to unload the starting material from the reactor at an appropriate time, and the use of ^{50}Cr in the form of chips then the choice actually has to be heavy water reactor L-2. It follows from the calculation [17] (see Table 3), that expected activity of ^{51}Cr after irradiation of 35.6 kg of enriched chromium in the standard mode of the reactor L-2 is 8.5 MCi, and can be reached 10 MCi (in modified mode of the reactor L-2).

Table 3. Results of ^{51}Cr production with a heavy water reactor L-2 [17].

site of target	number of channels	activity MCi	specific activity, Ci/g
Standard mode. Irradiation time is 130 days			
neutron traps	6	6.4	270
core	3	2.1	180
total	9	8.5	240
Standard mode. Irradiation time is 50 days (end of reactor campaign)			
neutron traps	6	5.3	220
core	3	1.7	140
total	9	7.0	200
Modified mode with the reduced loading fuel. Increasing of the reactor power 10%. Irradiation time is 130 days.			
core	9	9.7	270

2.2. Artificial source on the base of ^{75}Se.

^{75}Se is produced by neutron capture on ^{74}Se with the high cross section for thermal and epithermal neutrons (51.8 barns and 520 barns accordingly). Source material should be enriched in ^{74}Se and depleted in ^{76}Se, because of the high cross section of last isotope (85 barns). Fortunately for us enrichment procedure can be carried out by gaseous centrifugation of volatile SeF_6. An optimum value of enrichment of Se in ^{74}Se is of the order of 90%.

Starting material will present in form of tablets of pressured high purity Se powder, sealed into the hermetic shell of high pure grade of Al. The size of the tablets are less than

5-6 mm in order to avoid the effect of self-shielding of ^{74}Se. Table 4 presents the results of the ^{75}Se production with the reactor L-2 [18].

Table.4. The ^{75}Se production with the reactor L-2. Isotopic composition of starting material is ^{74}Se - 90%, ^{76}Se - 10%.

target type	specific activity, Ci	mass for 1 MCi, kg,
⌀3x3 mm	875	1.26
⌀5x5 mm	737	1.5

Conclusion

Calibration of detectors with ANS with well determined characteristics with accuracy not worse 5% is the necessary stage of next generation of solar neutrino experiments.

The experiments with GNO, BOREXINO and LENS detectors can be carry out with the same ANS based on ^{51}Cr if its activity at the time of a reactor shut down will be $\geq$ 8.9 MCi. The activity of the same ANS based on ^{75}Se which can be used for GNO and LENS experiments should be more than 3.48 MCi.

The best way to produce ^{51}Cr source with the activity up to 10 MCi is to use the russian heavy water reactor L-2. The starting material for this purpose is 35.6 kg of ^{50}Cr, which have been used before by GALLEX Collaboration.

The specific activity of ^{75}Se which can be produced with the reactor L-2 is 740-900 Ci/g, resulting a total activity, sufficient for the experiments in Gran Sasso laboratory, which were discussed in this report.

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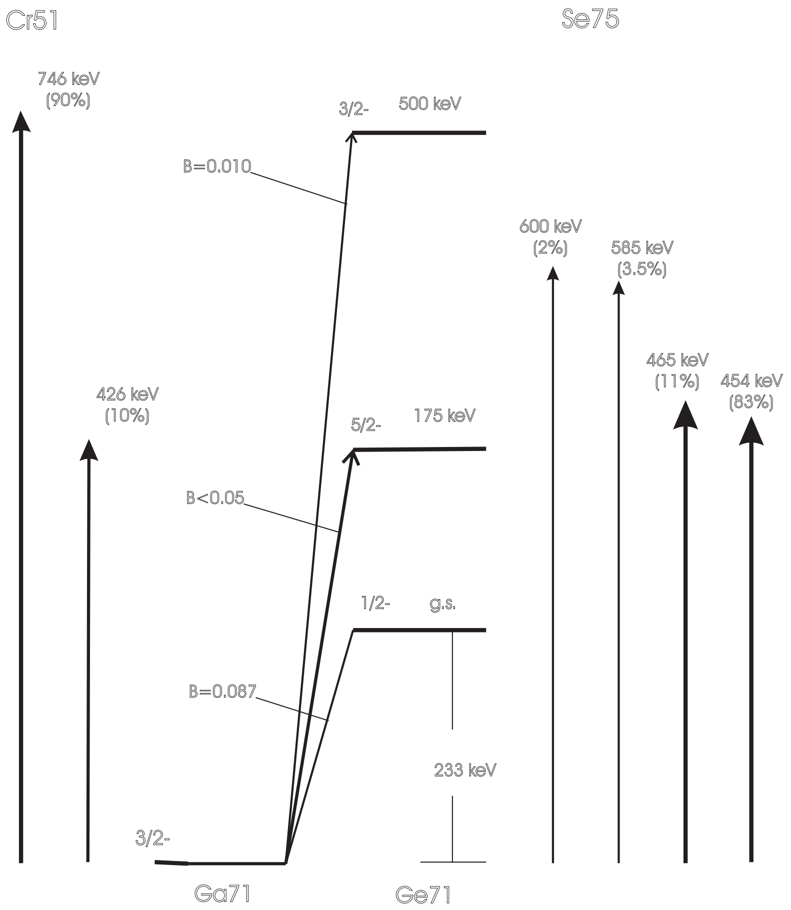

Fig.1.Nuclear data for the Ga-Ge detection of 51Cr and 75Se neutrinos.

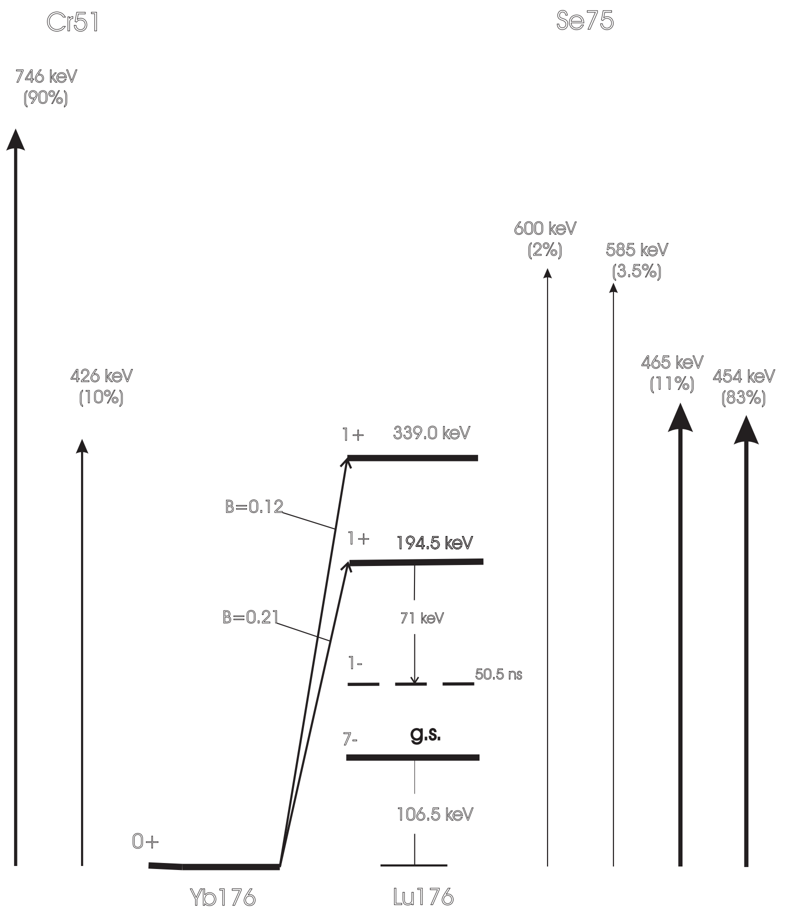

Fig.2.Nuclear data for the Yb-Lu detection of 51Cr and 75Se neutrinos.

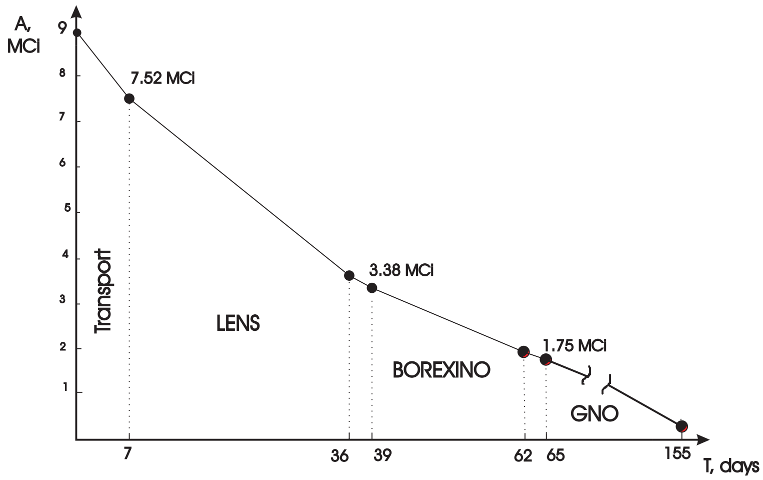

Fig3a. Cr51 experiment

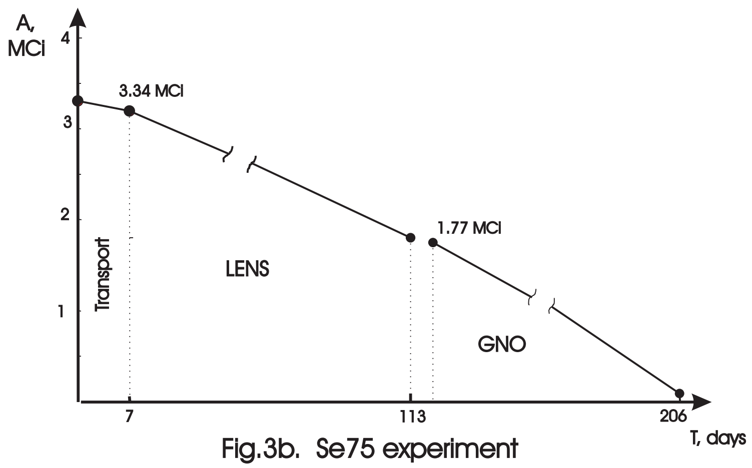

Fig.3b. Se75 experiment