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^{75}Se as a New Neutrino Source for Calibration of Solar Neutrino Detectors

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A new artificial neutrino source is considered on the basis of isotope ^{75}Se for the calibration of low threshold detectors of solar neutrino GNO, SAGE and LENS. ^{75}Se source has a number of advantages over the source on the basis of ^{51}Cr: the energy of its basic neutrino lines is close to the upper threshold of neutrino pp - cycle, and cross-section for its production and half-life are several times higher. The results of calculations demonstrating a possibility of ^{75}Se source production with the required activity on the heavy water reactor L-2 are presented.

^{75}SE КАК НОВЫЙ ИСТОЧНИК НЕЙТРИНО ДЛЯ КАЛИБРОВКИ ДЕТЕКТОРОВ СОЛНЕЧНЫХ НЕЙТРИНО

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Рассмотрен новый искусственный нейтрино источник на основе изотопа ^{75}Se для калибровки низко-пороговых детекторов солнечного нейтрино GNO, SAGE и LENS. ^{75}Se источник имеет множество преимуществ перед источником на основе ^{51}Cr: энергия его основных нейтрино линий близка к верхнему порогу нейтрино pp - цикла, и сечение его образования и период полураспада - в несколько раз выше. Представлены результаты вычислений, демонстрирующие возможность производства ^{75}Se источника с требуемой активностью в тяжеловодном реакторе L-2.

Fig. - 1 , Ref. - 8.

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The problem of solar neutrino

For the solution of solar neutrino problem the continuation of Ga-Ge experiments (GNO [1] and SAGE [2]) are necessary for the increase of their accuracy, as well as the development of new experiments (detector LENS [3] with the target on the basis of Yb). The aim of LENS is the direct observation of energy-resolved spectrum of solar electron-neutrinos (ν_e)< 2 MeV and the measurement of the specific ν_e fluxes from the p+p, ^{7}Be and CNO reactions in the sun. The ν_e detection is based on charged current (inverse β-) transitions on a target of ^{176}Yb to exited levels in ^{176}Lu. The ν_e tag consists of a 72 keV γ-ray that cascades via an isomeric state with a time window of τ=50 ns. Thus the calibration of detectors (the measurement of the specific ν_e cross-sections) is possible with MCi-class artificial neutrino sources (ANS): ^{51}Cr ($T_{1/2}$=27.7 d; E_ν =0.426 (10%), E_ν =0.751(90%)); and ^{75}Se ($T_{1/2}$=119 d; E_ν =0.465 (96%)).

The advantages of ^{75}Se over ^{51}Cr are in 4.3 times higher half-life and in the proximity of the energy of its neutrino lines to the upper threshold of pp-neutrino of solar cycle. The estimates has shown that 5% accuracy of calibration is provided by the following activities of ^{75}Se based ANS:

LENS -3.5 MCi; GNO - 1.8 MCi; SAGE - 0.5 MCi.

The physical properties of ^{75}Se

The production of isotope ^{75}Se is based on ^{74}Se (n,γ)^{75}Se reaction. The (n,γ) cross-section of ^{74}Se for thermal neutrons (at V=2200 m/c) is 51.8 barns and the resonance integral is equal 520 barns. The target nuclide ^{75}Se by means of K-capture converts into ^{75}As with the half-life 119.79 days. The maximum energy of β-radiation is 863.6 KeV. The decay is accompanied by the emission of neutrino with the energy 463 KeV, and also of electrons of internal conversion, X-rays and γ-rays emission with the average energy 0.216 MeV.

The manufacturing of selenium enriched by isotope ^{74}Se to 90-95% has no principled technical obstacles, but by the cost reasons, apparently, it is reasonable to be restricted by the enrichment shown above.

The selenium is very active chemically, therefore under conditions of irradiation and further utilization it should be enclosed in a hermetic shell, the admixtures of which can create an additional radioactivity.

The advantages of reactor L-2 [4] for the irradiation of selenium over other reactors - SM-3, MIR and BN-600, - are the following: large amounts of target material can be loaded in the reactor; the duration of fuel cycle (about 130 day) is comparable to the half-life of ^{75}Se (119.79 days), rather high neutron flux with low value of the hard component (1-2×10^{14} 1/cm^{2}s thermal flux) provides high specific activity (about 1000 Ci/g), the heat released in the targets during irradiation in the reactor can be easily removed. A possibility for 300 PBk ^{51}Cr based neutrino source production in L-2 reactor has been studied in [5].

The model of irradiation

The selenium enriched by ^{74}Se to 90% (^{76}Se - 10 %) was chosen as target material. Neutrino source represents an assembly of so-called liners aluminum hollow cylindrical cartridges, in which the capsules with selenium are disposed. Under irradiation in reactor the liners are disposed in block -absorbers. In neutrino source the irradiated liners constitute a hexagonal lattice of cylindrical elements (columns). Maximum number of columns is 19. Each column consists of 4 liners disposed one above another. The total number of liners is 54 pieces. Each liner contains 57.6 g of selenium. The sizes of the liner: diameter 48×28 mm, height 115 mm. During irradiation the surfaces of the liners have no contact to reactor water. After irradiation the liners are extracted from block-absorbers and are disposed in the neutrino source.
The chosen variant of neutron source reduces a possibility of contaminating of capsules by radioactive products of reactor origin and simplifies procedures on prevention and removal of similar contamination. Besides the solution of heat removal problem becomes simpler.
3 cases of channels irradiation - in neutron traps, in the core and in the reflector , - were investigated.

The 3D time-space simulation of fuel cycle of the reactor L-2 with some channels charged with selenium was performed by means of TRIFON [6] and SHERHAN [7] computer codes.

The results of calculations

The calculations were performed for fuel cycle having the duration 130 day and for 2 fuel cycles separated by time interval of 20 day when the reactor was shut down.

The basic results of computer simulation are presented in the Fig. 1 and in Tables 1, 2. As it follows from the results of calculations, the maximum values of specific activity are reached in the lower part of the reactor, therefore in Fig. 1 the accessible values of average specific activity are also shown for the case of the displacement of targets to the bottom part of the reactor.

The values of specific activity of target material in channels placed in neutron traps of the core, in average conditions in the core and in the side reflector after the irradiation during one and two fuel cycles are presented in the Table 1.

The numbers of channels for the production of ANS with the total activity 1 MCi and 3.5 MCi as well as the masses of the required selenium: 1.0-1.4 kg and 3.2-4.2 kg respectively, - are presented in the table 2.

Table 1. Average specific activity of ^{75}Se (Ci/g) for irradiation of channels in neutron traps, in the core and in the reflector.

Target	2x2 (5x7) mm		
Time of irradiation, days (number of fuel cycles)	Trap	Core	Reflector
130 (1)	870(570)	770 (500)	420 (280)
280 (2)	1230 (810)	1100 (715)	600 (400)

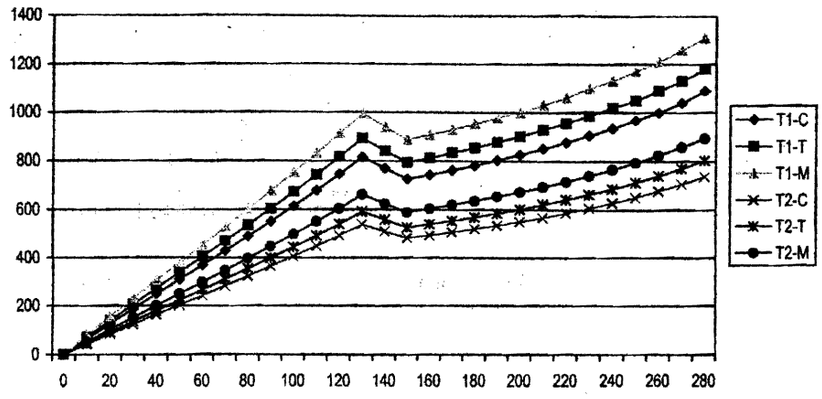

Fig. 1. The dependence of specific activity (Ci/g) on irradiation time (days) for targets T1 and T2; C - core, T - trap, M - maximum achievable values in the trap. T1, T2 - targets 2×2 mm, 5×7 mm containing 0.0286 g, 0.6 g of selenium respectively.

Table 2. The mass of enriched selenium (kg) and the number of channels required for the production of ANS with the total activity 1 MCi and 3.5 MCi.

	≈ 1 MCi			≈ 3.5 MCi		
Target	Numb. of channels	Mass kg	Activity MCi	Numb. of channels	Mass kg	Activity MCi
2x2	12(6*+6)	0.888	1.024	42(6+36)	3.108	3.476
5x7	3 (3+0)	1.296	1.049	11(6+ 5)	4.752	3.645
5x7	4(0+4)	1.728	1.235	12(0+12)	4.146	3. 707

*) First number - in the trap, second - in the core

The results of reactor tests

3 selenium blocks with targets 1×1, 2×2 and 3×3 mm were irradiated in the neutron trap of reactor L-2 during 10 months in the period from 21.05.97 to 10.03.98. The cylindrical annular blocks were used in the test. An aluminum inlay with vertical holes was inserted into aluminum annular block. Target material - extruded powder-like fine-dispersed metal of highly enriched selenium (98% ^{74}Se) - was embedded in Ti capsules and sealed hermetically by argon-arc welding. The capsules were put into the holes of the inlay. The blocks were irradiated at the bottom part of the channel in the region of maximum neutron flux. The basic results of reactor tests are presented in the table 3. The following designations are used: d - sizes of targets, diameter×height, τ - time of irradiation (effective and calendar days), DER - dose equivalent at the distance 1 m from the side of titanium capsule on the 20th day from the date of discharge from reactor, A - specific activity of the target (conversion factor - 3.85× 10^{-19} A / (kg Bk)). The experimental error of DER measurement was about 16 %.

Table 3. The results for reactor test.

Target parameters		τ eff. days	τ days	DER, μA/kg	A* Ci/g	A-calc. Ci/g
d, mm	mass, mg					
1x1	3.6	102.5	162	0.0417	812	-
2x2	28.8	189.6	292	0.3370	824	920
3x3	97.2	189.6	292	1.1200	804	-

(* Neglecting self- absorption of γ rays by Se and Ti).

The calculated estimated value A-calc. of 2×2 mm target activity, obtained with the corrections for the differences in ^{74}Se enrichment and flux levels is also presented in the table 3.

The calculated result is consistent with the results of reactor tests within the experimental errors.

The activity of impurities

The composition of aluminium with impurities is presented in Table 4, γ-radiation of the source - in table 5.

Table 4. The composition of aluminium with impurities (mass %).

Al	Fe	Si	Cu	Mn	Zn	Ti	Mg	Cd	B
99.5159 87	0.09-0.22	0.069-0.165	0.01 3	0.00 8	0.03 7	0.005 7	0.03 5	0.0000 63	0.0002 5

For the source of total activity A = 3,5×10^6 Ci the mass of a selenium is equal M= 3108 g; total mass of aluminum in the source M_{Al} = 32240 g.

Table 5. Gamma radiation of the irradiated source (radiation of impurities with Eγ >0,55 MeV), normalized to the source activity 3,5× 10^6 Ci.

Isotope	Activity, Ci	$T_{1/2}$	Eγ, MeV,	NγEγ, MeV/decay	Q, MeV/sec
^{56}Mn	2580	2.58 hours	0.84 1.81 2.11	0.832 0.416 0.295	7.94×10^{13} 3.97×10^{13} 2.82×10^{13}
^{65}Zn	120	245 d	1.11	0.555	2.46×10^{12}
^{59}Fe	14.8	45 d	1.10 1.29	0.616 0.568	3.37×10^{11} 3.11×10^{11}
^{46}Sc	0.11	84 d	0.89 1.12	0.89 1.12	3.62×10^{9} 4.56×10^{9}
^{31}Si	38	2.62 hr	1.26	0.0882	1.24×10^{11}
Se isotopes	3.5×10^6	118.5 d	0.572 0.618 0.822	2.037×10^{-4} 2.743×10^{-5} 1.126×10^{-6}	2.64×10^{13} 3.55×10^{12} 1.44×10^{11}

Dose intensities

The dose intensity for the container of biological shielding with thickness 9 cm, made of alloy of tungsten with density 17.9 g/cm^3, is presented in table 6.

Table 6. Dose intensity on the surface of container D_1 (upper values) and at the distance 2 m from the surface of container D_2 (lower values), μSv/ hr; T - time after irradiation, days.

T\ Isotope	^{56}Mn	^{65}Zn	^{59}Fe	^{31}Si	Se	^{46}Sc	^{60}Co
0	7.4×10^4	91.4/8.7	46.8/ 4.4	11.8/ 1.12	0.220/ 0.0036	0.180/ 0.017	0.055/ 0.0052
10	-	88.9/8.5	39.4/ 3.8	-	0.200/ 0.0034	0.166/ 0.016	0.055/ 0.0052
100		68.9/6.6	10./ 0.94		0.123/0.002	0.079/ 0.0074	0.055/ 0.0052

The permissible dose intensity on the surface of container recommended by the LNGS authorities is 200 μSv/ hr. The permissible dose intensity at the distance 2 m from the surface of container recommended by the LNGS authorities is 2.5 μSv/hr.

Heat release in the source and biological shielding

The total thermal power released due to the decay of ^{75}Se at the source activity 3.5 MCi, constitutes 7640 W. The power released in the source is equal 4905 W, in the biological shielding - 2735 W. The results of heat calculations are shown in table 7.

The rate of a heat-up of the liner with no heat removal constitutes 0.26 °C/s.

The technology of selenium purification from admixtures is well developed [8] and it can be deeply purified from admixtures leading to the accumulation of dangerous radio nuclides (Fe $\leq 2\times10^{-5}$%, Ga $\leq 10^{-5}$% , Cd $\leq 10^{-5}$% , As $\leq 10^{-4}$%, Ag $\leq 10^{-5}$ %).

Due to high half-life of ^{75}Se there exists a possibility of its storage for about 3 weeks up to complete decay (or considerable reduction of activity) of possible short-lived impurity isotopes. At the same time the activity ^{75}Se itself is reduced only by 12 %.

Table 7. The results of heat calculations.

	Cooling by water	Cooling by air
Coolant flow rate, kg/hour	2700	450
Coolant input temperature, °C	25	25
Heating , °C	1.5	31
Overfall temperature drop coolant- liner, °C	69	108
Overfall temperature drop liner - capsule, °C	14	14
Maximum temperature of capsule, °C	109	174

Conclusions

A new artificial neutrino source is considered on the basis of isotope ^{75}Se for the calibration of low threshold detectors of solar neutrino GNO, SAGE and LENS. ^{75}Se source has a number of advantages over the source on the basis of ^{51}Cr: the energy of its basic neutrino lines is close to the upper threshold of neutrino pp - cycle, and cross-section for its production and half-life are several times higher.

It enables to put much lower requirements to the time frameworks for the experiment realization. The target material of high purity having small amounts of dangerous admixtures can be prepared.

The production of ^{75}Se with the required total activity 1 MCi - 3.5 MCi (at the average specific activity 800-1200 Ci/g) can be realized on the heavy water reactor L-2. For this purpose 1.0 - 4.5 kg of selenium, enriched to 90-95 % by ^{74}Se, should be loaded in the reactor and irradiated for 1 (130 days) or 2 (280 days) fuel cycles. In this case the accuracy no lower than 5% for neutrino detectors LENS, GNO and SAGE calibration can be provided.

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