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^{7}Li solar axions: Preliminary results and feasibility studies

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Abstract

Feasibility studies on a search for ^{7}Li solar axion have been carried out. In particular, the data collected with a LiF powder of 243 g measured during 722 h with a 408 cm^3 low background HP Ge detector (GSOR) at the Gran Sasso National Laboratories (LNGS) of INFN has allowed to set limit on the ^{7}Li solar axion mass of 13.9 keV, better than the previously available one: 16.0 keV [A.V. Derbin, et al., JETP Lett. 81 (2005) 365]. It has also been shown that improved results would be achieved with LiF(W) crystal which—in contrast with the LiF powder—does not show a relatively high contamination by U/Th chains. The potential backgrounds and the reachable sensitivity of an experiment are discussed.

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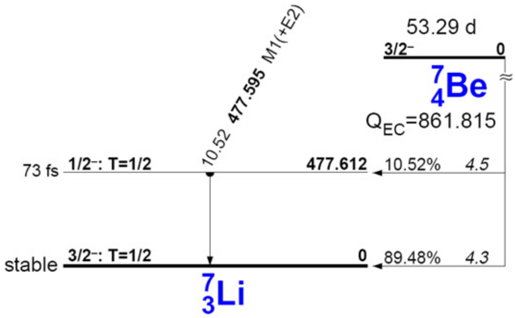

Fig. 1. Decay scheme of ^{7}Be in accordance with [10].

1. Introduction

The axion is a hypothetical particle which was proposed to solve the so-called problem of CP violation in strong interactions (see [1,2] and references wherein). If it exists, Sun could be an intensive source of axions. Energy spectrum of solar axions would consists of the continuous part generated via the Primakoff effect, and quasi-monochromatic lines related with deexcitation of excited levels of nuclides present in Sun through magnetic nuclear transitions. These levels can be thermally excited because of high temperature in the solar core, or can be populated in nuclear reactions. In a deexcitation process, axions could be emitted instead of γ quanta with some probability which is related to the axion mass. Note that the scale, f_a, of the Peccei–Quinn symmetry breaking fixes the axion mass: $m_a \simeq 0.62$ eV $\times$ $(10^7$ GeV$/f_a)$; however, the theory does not provide restrictions on f_a [1,2].

Expected axion fluxes from the thermally excited first levels of ^{23}Na ($E_{\rm exc} = 440.0$ keV), ^{55}Mn ($E_{\rm exc} = 126.0$ keV) and ^{57}Fe ($E_{\rm exc} = 14.4$ keV) in Sun were calculated in [3]; the flux from ^{57}Fe was estimated as the biggest one because of relatively low excitation energy. A novel experimental scheme of searching for such axions was proposed in [4]: when resonant conditions are fulfilled, the incoming solar axion can excite the same nucleus at long distance at Earth. Particles emitted in nuclear deexcitation process (γ quanta, conversion electrons, etc.) can be observed with a proper detector where, for ^{57}Fe case, peak at energy of 14.4 keV should be found. The first experiment investigating ^{57}Fe solar axions [5] did not find the expected peak producing only limit on the ^{57}Fe solar axion mass: $m_a < 745$ eV at 95% C.L. Very recently, this limit was improved to values of 360 eV [6] and 216 eV [7].

Axions possibly emitted in deexcitation of thermally excited ^{83}Kr in the solar core ($E_{\rm exc} =$ 9.4 keV) were searched for in Ref. [8]; an upper limit on hadronic axion mass of 5.5 keV was obtained at 95% C.L.

M1 transitions from the first excited level of ^{7}Li ($E_{\rm exc} = 477.6$ keV) in solar core also could be source of quasi-monochromatic axions [9]. This ^{7}Li* level is populated in pp chain of nuclear reactions in Sun when ^{7}Be nucleus, produced through the ^{3}He $+ \alpha \to {}^7$Be $+ \gamma$ reaction, decays to ^{7}Li; the 477.6 keV level of ^{7}Li is occupied with 10.5% probability (Fig. 1).

Coming to Earth, these axions can be resonantly captured by ^{7}Li nuclei. In the subsequent deexcitation process, γ's of 477.6 keV will be emitted (electron conversion coefficient is very low: 7.3×10^{-7} [11]), and, therefore, the possible presence of such axions can be singled out by the presence of the characteristic peak in the energy distribution of a suitable detector placed close to or containing the ^{7}Li sample. The total number of resonant axion absorption processes in a ^{7}Li sample, containing N_7 number of ^{7}Li nuclei, has been calculated [9,12] by taking into account the current Solar Standard Model as:

$$R = N_7 \times t \times 1.74 \times 10^{-45} \times \left(\frac{m_a}{1\ \text{eV}}\right)^4; \tag{1}$$

here t is the time of measurements (in seconds). In case no evidence is found for the peak searched for, an upper limit on m_a can be set straightforward.

The first experimental work, searching for the ^{7}Li solar axions, gave only the limit: $m_a <$ 32 keV [9]. Later it was improved to the value of 16 keV [12]. As one can see, m_a limits from ^{7}Li are higher than those obtained in experiments with ^{83}Kr ($m_a < 5.5$ keV [8]) and ^{57}Fe ($m_a <$ 216 eV [7]). Nevertheless, they are important because of the following reason: if the hadronic axion mass is higher than excitation energy of ^{83}Kr ($E_{\text{exc}} = 9.4$ keV) or ^{57}Fe ($E_{\text{exc}} = 14.4$ keV), axions just will not be produced in the ^{83}Kr* and ^{57}Fe* transitions. In addition, the ^{7}Li limits are related with the pp chain, the main source of the solar energy, while the ^{57}Fe and ^{83}Kr bounds are subjected to some uncertainties in determination of the iron and krypton abundances in the solar core.

Not only the Sun but also nuclear reactors and artificial radioactive isotopes, as sources of intensive nuclear magnetic transitions, were used in searches for axions. Among many different experimental approaches [2], we mention here search for missing γ quanta in decay of ^{139}Ce [13] where limit $m_a < 26.7$ keV was set. In nuclear reactor experiments [14,15], two γ quanta created in decay $a \to 2\gamma$ were searched for in coincidence; sum of energies of these γ's should be equal to energy of nuclear transition in which the axion was emitted. Among the best, limit $m_a < 60$ keV should be referred [14]. Searches for axions with $m_a > 1022$ keV via decay $a \to e^+e^-$ were performed [16], also with negative result. Recently, monoenergetic lines produced by the Primakoff and Compton conversions of axions emitted from the Kuo-Sheng nuclear power reactor were searched for with a HP Ge detector; axions with masses 10 keV $< m_a <$ 1 MeV were excluded [17].

Here, with the aim to preliminarily investigate the ^{7}Li solar axions, measurements on some LiF samples were carried out by using two low background HP Ge detectors in underground conditions (3600 m w.e.) at the Gran Sasso National Laboratories of INFN: GSOR (408 cm^3) and GEBER (244 cm^3) as described in the following. The potential backgrounds and the reachable sensitivity of an experiment have also been analysed.

2. Measurements with LiF samples

Three LiF samples were investigated: two LiF powders of different production (243 g and 47 g, respectively) and a LiF(W) crystal (224 g).

Let us firstly examine the results obtained using a LiF powder (purity of 99.99%) with mass of 243 g; it was measured in the low background set-up with the 408 cm^3 HP Ge detector (GSOR) during 722 h.

Comparison of the measured LiF spectrum with the GSOR background shows that the sample is heavily polluted by isotopes from ^{232}Th and ^{238}U chains. Fig. 2 (top) shows the energy distributions measured with and without (background) the LiF sample for the whole energy range, while Fig. 2 (bottom) shows the same for the energy range around the 477.6 keV peak searched for.

All peaks in the LiF sample were identified; they belong to usual contaminants: nuclides from U/Th chains, ^{40}K, ^{60}Co, ^{137}Cs. Comparing rates of the peaks in the LiF sample and in the GSOR

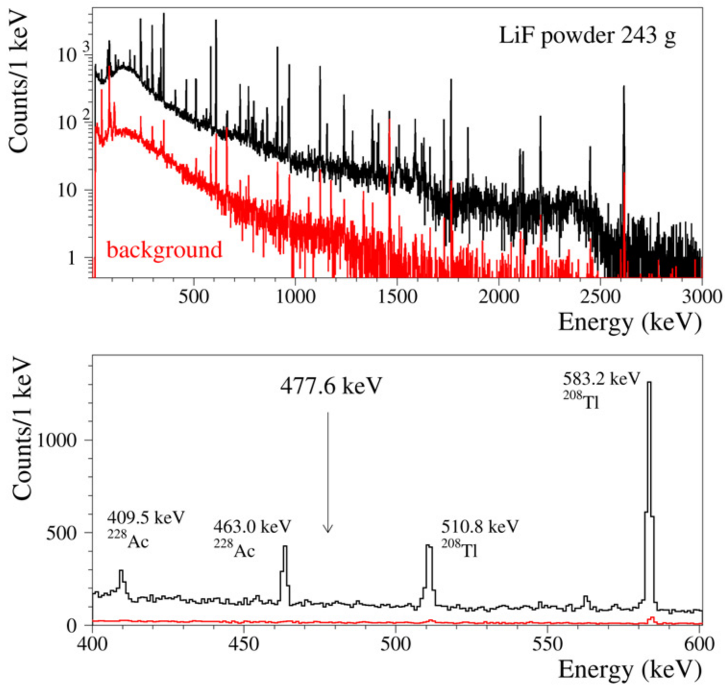

Fig. 2. Energy distribution measured with the LiF sample (243 g) by the LNGS HP Ge GSOR detector (408 cm^3) during 722 h in comparison with the background measured during 1571 h (normalized here to 722 h).

background, one can calculate activities as:

$$A = (S_{sample}/t_{sample} - S_{bg}/t_{bg})/(y \cdot \epsilon \cdot m),$$

where S_{sample} (S_{bg}) is the area of a peak in the sample (background) spectrum; t_{sample} (t_{bg}) is the time of the sample (background) measurement; y is the yield of the corresponding γ line [10]; ϵ is the efficiency of the full peak detection; m is the mass of the sample. Efficiencies were calculated with the GEANT4 package [18]. Summary of activities is given in Table 1, with values on the level of up to $\simeq 0.5$ Bq/kg for U/Th nuclides but only with limits for ^{40}K, ^{60}Co, ^{137}Cs and ^{207}Bi.

Then, measurements with a LiF powder (mass of 47 g) from a different party was performed with the same 408 cm^3 GSOR detector during 914 h. This sample also shows quite high U/Th contamination (however, near 2–3 times lower than the first one), while also only limits on ^{40}K, ^{60}Co, ^{137}Cs and ^{207}Bi were determined.

Finally, a LiF(W) crystal with mass of 224 g was measured with the LNGS low background HP Ge detector GEBER (244 cm^3) during 633 h. The crystal was produced by the Czochralski method in the Institute for Scintillation Materials (Kharkiv, Ukraine). To improve its scintillation properties, it is doped by W at level of 0.04%.

Comparison of the measured LiF(W) spectrum with the GEBER background is shown in Fig. 3. Immediately it could be seen that—in contrast with the LiF powders—the LiF(W) crystal is very pure: the energy distribution measured with the sample practically coincides with the background. Only limits for radioactive pollutions were derived (see Table 1).

Table 1
Radioactive contaminations in the LiF samples. Limits are given at 90% C.L.

Chain	Nuclide	Activity, Bq/kg		
		LiF powder 1 243 g	LiF powder 2 47 g	LiF(W) crystal 224 g
^{232}Th	^{228}Ac	0.48(1)	0.17(1)	<0.02
	^{208}Tl	0.11(1)	0.04(1)	<0.02
^{238}U	^{214}Pb	0.58(1)	0.31(1)	<0.02
	^{214}Bi	0.55(1)	0.28(1)	<0.02
	^{40}K	0.064(16)	<0.110	<0.066
	^{60}Co	<0.001	<0.001	<0.002
	^{137}Cs	<0.001	<0.001	<0.003
	^{207}Bi	<0.005	<0.003	<0.005

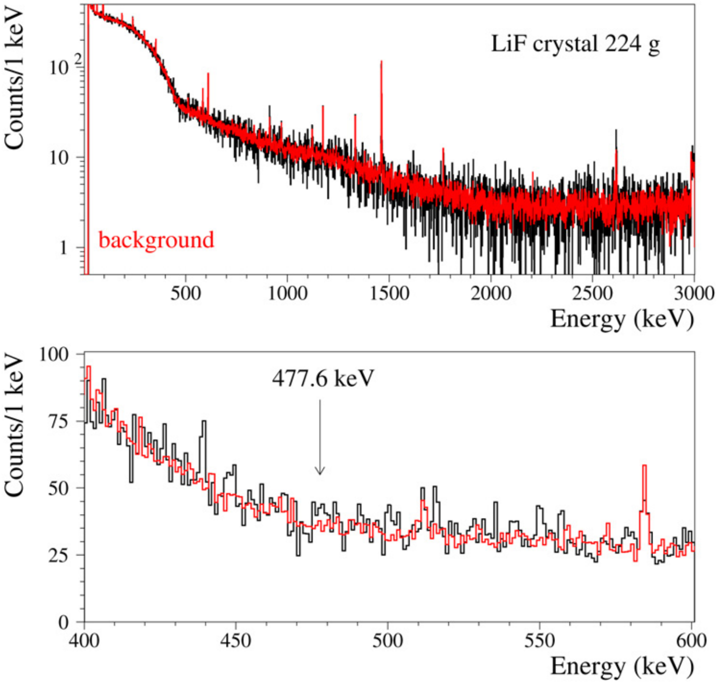

Fig. 3. Energy distribution measured with the LiF(W) crystal (224 g) by the LNGS HP Ge GEBER detector (244 cm^3) during 633 h in comparison with the background measured during 3047 h (normalized here to 633 h).

3. Limit on the ^{7}Li solar axion mass

Using Eq. (1) [9,12], the ^{7}Li solar axion mass can be obtained:

$$m_a = 1.55 \times 10^{11} \times \left(\frac{S}{\varepsilon N_7 t}\right)^{1/4} \text{ eV}; \tag{2}$$

here S is the area of the 477.6 keV peak (or its limit), ε is the detection efficiency for such a peak, N_7 is the number of ^{7}Li nuclei, and t is time in seconds.

In the spectrum collected with the LiF powder sample of 243 g during 722 h peak at energy of 478 keV is absent (see Fig. 2 (bottom)), and we can set only the limit on its area with some confidence level. In the so-called "one sigma approach", the excluded number of real events that could be invisible in the spectrum is estimated simply as square root of the number of background counts in a suitably chosen energy region. Taking into account that the peak width (FWHM) at energies near 478 keV is $\simeq 2$ keV and number of counts in the 475–480 keV energy window is equal to 565, we get the limit on the S value as 39 at 90% C.L. Further, using the standard least square procedure, the experimental spectrum in the range of 440–550 keV was fitted by the sum of the straight line (representing the background here) and three Gaussians at energies of 463 keV, 478 keV and 511 keV. As a result of the fit, the obtained area for the 478 keV peak is equal to -5 ± 17 counts, giving no evidence for the effect. The maximum number of excluded events was calculated with the Feldman–Cousins procedure [19] as 23 at 90% C.L. Using the more cautious value of $\lim S = 39$ obtained in "one sigma approach" and efficiency of the 478 keV peak detection of 4.4%, we get the limit on the axion mass as:

$$m_a < 13.9 \text{ keV} \quad \text{at 90\% C.L.}$$

Data collected with other two LiF samples were processed in a similar way. However, obtained m_a limits were slightly worse: $m_a < 15.3$–15.5 keV. This is related with lower mass of the sample (47 g instead of 243 g) measured with the GSOR detector, or with lower efficiency of the GEBER detector which was used to measure pure 224 g LiF(W) crystal.

The obtained value of 13.9 keV is better than the best previous limit of 16.0 keV obtained for the ^{7}Li solar axion mass in the experiment of ref. [12]. While this improvement is modest, nevertheless it is important because it closes the existing window of possible axion masses between the previous limit of 16.0 keV and the 14.4 keV energy of the next potential source of quasi-monochromatic solar axions from ^{57}Fe.

4. Estimation of backgrounds and experimental sensitivity

The excited level of ^{7}Li with $E_{exc} = 477.6$ keV can be populated not only because of resonant capture of ^{7}Li solar axion, but also in a few other reactions. As well, events with energy near 478 keV could be produced by radioactive decays of some nuclides present in a detector components and shielding, or in the LiF sample itself. All these background sources could prevent to reach high sensitivity in searching for the solar axions; it is therefore important to estimate the level of expected backgrounds from the different sources.

(1) *Capture of neutrons by* ^{6}Li: $n + {}^6\text{Li} \to {}^7\text{Li}^*$. After a n capture, the daughter nucleus ^{7}Li will be in an excited state. In the deexcitation process γ quantum with energy of 7245.9 keV (62%) or a cascade of two γ's of 6768.8 keV and 477.6 keV (38%), respectively, will be emitted [20].

The number of n captures is equal to:

$$N = f \cdot \sigma \cdot N_n \cdot t, \tag{3}$$

where f if the neutron flux in the Laboratori Nazionali del Gran Sasso, σ is the cross section of neutron capture, N_n is number of ^{6}Li nuclei, and t is time of measurements.

Thermal neutron flux underground in the LNGS was measured to be $f = (1.08 \pm 0.02) \times 10^{-6}\ \text{cm}^{-2}\,\text{s}^{-1}$ [21], however the flux reaching a detector inside a suitable neutron shield will be significantly reduced by factors, which depend on the performances of the used shield. However, to be very conservative, in the following we will overestimate the f value assuming it even at the value of the total n flux in LNGS: 3.8×10^{-6} cm^{-2} s^{-1} [21,22].

The new value for n cross section with ^{6}Li is 52.6 mb [20], near 30% higher than the old one (39 mb, see f.e. [10]). The number of ^{6}Li nuclei (natural abundance of ^{6}Li is 7.59% [23]) in 600 g LiF sample (which is a conservative upper limit for mass of a sample which can be adopted with the GSOR and GEBER detectors) is: $N_n = 1.06 \times 10^{24}$. Under these extremely conservative assumptions, the n capture rate in the 600 g LiF sample is: $N/t = 2.1 \times 10^{-7}$ 1/s, or, during $t = 6$ months: $N = 3.3$ captures, and the number of 478 keV gamma quanta emitted will be equal to 1.3. Since the efficiency of registration is $\sim$ 2–5% (depending on the used detector), it will give $\simeq 0$ counts in the measured energy distribution.

(2) *Excitation of* 477.6 keV *level of* ^{7}Li *by fast neutrons* ($E_n > 478$ keV) *and cosmic muons*. In the experiment of Ref. [12], which was performed at the Earth level, the 478 keV peak was really observed—in coincidence with the active shielding; thus one can conclude that it was related with cosmic muons. The number of events was equal to 840 for 126.5 days of measurements with the 3.9 kg LiOH sample. At LNGS the flux of cosmic muons is suppressed by a factor of 10^6 and the flux of neutrons with energy $E_n > 0.5$ MeV is near 2×10^{-6} cm^{-2} s^{-1} [21,22], suppressed by factor 10^3 in comparison with that at the Earth level [24]. Thus, even neglecting the use of a suitable neutron shield, one can expect that the corresponding number of events in the underground measurements will be negligible.

An additional argument is given in the following. High energy muons and neutrons will excite not only ^{7}Li but also other nuclei, in particular, the most abundant Ge isotopes present in Ge detectors: ^{72}Ge (abundance $\delta = 27.54\%$, energy of the first excited level $E_{\mathrm{exc}} = 691.4$ keV) and ^{74}Ge ($\delta = 36.28\%$, $E_{\mathrm{exc}} = 595.9$ keV). The corresponding peaks are present in the energy distributions measured by Ge detectors at the Earth level (see f.e. [12]), Doppler broadened because of movement of nuclear recoils. However, they are not evident in the background spectra of the GSOR and GEBER detectors measured deep underground during 1571 h and 3094 h, respectively.

(3) *Excitation of the* 477.6 keV *level of* ^{7}Li *by* α *and* ^{3}H *particles from reaction* $n + {}^6\mathrm{Li} \to {}^3\mathrm{H} + \alpha$. The cross section for this reaction is high: 940 b [10] (compare with 52.6 mb for the $n + {}^6\mathrm{Li} \to {}^7\mathrm{Li}^*$ process). Thus, the rate of this reaction for the overestimated n flux in the detector (see above) of 3.8×10^{-6} cm^{-2} s^{-1} and 600 g of LiF sample is: $N/t = 3.8 \times 10^{-3}$ 1/s, giving rise to $N = 5.9 \times 10^4 \alpha$ (and ^{3}H) particles during $t = 6$ months.

With an effective area of the 600 g LiF sample of 100 cm^2, flux of such α and ^{3}H particles is 3.8×10^{-5} cm^{-2} s^{-1}. If we accept the value $\sigma = 100$ mb for excitation of the ^{7}Li to ^{7}Li* by such α particles [12], with 1.29×10^{25} nuclei of ^{7}Li in the 600 g LiF sample, we will obtain—under the above extremely conservative assumptions—a rate of ^{7}Li* creation: $N/t = 4.9 \times 10^{-5}$ 1/s, or, during $t = 6$ months: $N = 760$ events. If the cross section of ${}^7\mathrm{Li} \to {}^7\mathrm{Li}^*$ excitation by ^{3}H is near the same as for α particles, this number should be doubled.

Therefore, this mechanism can really create events imitating those from the capture of ^{7}Li solar axions. With $N < 10^3$ and efficiency of the registration by Ge detector $\simeq 4\%$, we will have near < 40 counts in the 478 keV peak due to this process during 6 months period. However, the real number of these events will not be so large both because of the used overestimate of the neutron flux and especially in comparison with the background of the GSOR and GEBER detectors (near 500 and 1000 events, respectively, in 475–480 keV region during 6 months).

(4) If in a detector shielding there is a material with *boron* content (f.e. B loaded polyethylene), neutron capture on ^{10}B (natural abundance is 19.9%) will lead to reaction: $n + {}^{10}\mathrm{B} \to {}^7\mathrm{Li}^* + \alpha$,

with subsequent emission of 477.6 keV gamma quantum. Intensity of the 478 keV line (broadened to $\simeq$ 470–487 keV energy range due to movement of ^{7}Li recoil [25]) will be related with amount of B in vicinity of a detector, but also with material and geometry of other shielding components. This line should be present also in absence of a LiF sample. This is not the case for the GSOR and GEBER detectors (see Figs. 2 and 3).

(5) *Neutron capture on* ^{113}Cd (its abundance is 12.22% in natural Cd which is often used as detector shielding) also will result in emission of γ 477.6 keV [20]. However, in this case also γ line at energy 558.3 keV should be present in spectrum with intensity higher by factor of $\simeq$ 150 [20]. This line is absent in the background spectra of the GSOR and GEBER detectors.

(6) *Other sources* related with specific detector and its shielding: lines with energies near 478 keV of any origin are not evident in the background spectra of the GSOR and GEBER HP Ge detectors (see Figs. 2 and 3).

(7) *The* LiF *sample itself* could be polluted by some long-lived cosmogenic or artificial sources, and by nuclides from natural U/Th chains which could emit 478 keV γ quanta. The inspection of the list of γ lines [10] gave the following potential sources:

– ^{102}Rh and ^{102m}Rh ($T_{1/2} = 207$ d and $T_{1/2} = 2.9$ yr, respectively): $E_\gamma = 475.1$ keV. It should be accompanied by other lines (f.e. 631.3 keV), however with lower intensities. It is impossible to check this hypothesis with current statistics collected with the GEBER detector (633 h). However, energy resolution could help to resolve this peak from the 477.6 keV peak;

– ^{134}Cs ($T_{1/2} = 2.062$ yr): $E_\gamma = 475.4$ keV with relative intensity $I = 1.46$. However, associated peaks with higher intensities are not evident in the LiF(W) crystal spectrum (f.e. $E_\gamma = 604.7$ keV, $I = 97.56$);

– ^{234m}Pa (^{238}U chain): $E_\gamma = 475.8$ keV, $I = 2.29$. However, it should be accompanied by a line with $E_\gamma = 1001.0$ keV, $I = 837$, which is absent in the LiF(W) crystal spectrum;

– ^{166}Ho ($T_{1/2} = 1200$ yr): $E_\gamma = 476.4$ keV, $I = 0.0363$. However, associated stronger peaks are absent (f.e. $E_\gamma = 810.3$ keV, $I = 58.08$);

– for the same reason should be rejected also ^{144}Pm ($T_{1/2} = 363$ d, $E_\gamma = 476.8$ keV), ^{150}Eu ($T_{1/2} = 35.8$ yr, $E_\gamma = 476.9$ keV), ^{211}Pb (^{235}U chain, $E_\gamma = 478.0$ keV), ^{154}Eu ($T_{1/2} = 8.593$ yr, $E_\gamma = 478.3$ keV), ^{228}Ac (^{232}Th chain, $E_\gamma = 478.3$ keV), ^{234}Pa (^{238}U chain, $E_\gamma = 478.6$ keV).

(8) *Cosmogenic activation of a* LiF *sample*. ^{7}Li* and ^{7}Be (which decays further into ^{7}Li* with probability of 10.52%) can be created in spallation reactions with cosmic muons on ^{19}F in LiF sample in course of an experiment. With μ flux of $\simeq 20$ m^{-2} d^{-1} at LNGS, only $\simeq 40$ muons will go through the 600 g LiF sample during 6 months. At the Earth level, in 1 kg of ^{19}F near 29 nuclei of ^{7}Be are created during 1 day (calculated with the COSMO code [26]). At LNGS, where muon flux is suppressed at 10^{6} times, this contribution will be negligible.

Creation of cosmogenic ^{10}B nuclei (dangerous because of $n + {}^{10}\text{B} \to {}^{7}\text{Li}^* + \alpha$ reaction) from ^{19}F at the Earth being, in accordance with the COSMO calculations, is very suppressed; thus LiF cannot be polluted by ^{10}B, at least because of cosmogenic reactions.

(9) *Reaction* $p + {}^{7}\text{Li} \to {}^{7}\text{Be} + n$ *with the subsequent decay of* ^{7}Be *to* ^{7}Li* *during measurements*. Flux of protons is related with flux of muons in the LiF sample which is very small; thus we can neglect by this contribution.

Let us now comment the potential sensitivity of the experiment in further measurements. It can be estimated in accordance with the measured background rate in the energy interval of 475–480 keV (0.285 counts/h for the GEBER 244 cm^{3} detector and 0.105 counts/h for the GSOR 408 cm^{3} detector) and expected efficiencies. In this way, a sensitivity on ^{7}Li solar axion mass of $\simeq 8$ keV can be obtained with the GSOR detector (which has lower background and higher efficiency) in data collection with a sample of pure LiF(W) crystal (with bigger mass, which is available) during 6 months. In addition, LiF(W) and LiI(Eu) scintillation crystals could be used to search for the ^{7}Li solar axions; this would allow to build a large scale experiment. To investigate radiopurity of LiI(Eu) scintillators, measurements of two LiI(Eu) crystals are in progress now.

5. Conclusions

The collected data with the LiF powder sample of 243 g measured during 722 h allowed to set limit on the ^{7}Li solar axion mass of 13.9 keV at 90% C.L., better than that from Ref. [12]: 16.0 keV. This modest improvement is nevertheless important because it closes the existing possible window between 16.0 keV and 14.4 keV, which is the energy of the next potential source of quasi-monochromatic solar axions from ^{57}Fe.

Measurements of different LiF samples showed that the LiF(W) crystal, in contrast with the LiF powders, is not contaminated by radioactive nuclides: the obtained limits are on the level of 20 mBq/kg for U/Th chains, and on the level of a few mBq/kg for ^{60}Co, ^{137}Cs and ^{207}Bi.

Background processes potentially contributing to the expected 478 keV peak from the ^{7}Li solar axions are estimated; in the LNGS underground conditions—assuming absence of a suitable neutron shield—the only ones to be accounted for (see previous section) are:

(1) possible pollution of the LiF sample by ^{10}B (because of reaction $n + {}^{10}\mathrm{B} \to {}^{7}\mathrm{Li}^* + \alpha$);
(2) excitation of the 478 keV level of ^{7}Li by α and ^{3}H particles from reaction $n + {}^{6}\mathrm{Li} \to {}^{3}\mathrm{H} + \alpha$.

Sensitivity of an experiment to the axion mass is calculated to be $\simeq 8$ keV after 6 months data collection with the GSOR detector. This value will be more confident than the current limit of 13.9 keV, which is still quite close to the ^{57}Fe energy of 14.4 keV, and will allow also to cover the ^{83}Kr energy of 9.4 keV.

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