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BEST potential in testing the eV-scale sterile neutrino explanation of reactor antineutrino anomalies

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Baksan Experiment on Sterile Neutrino (BEST) [Gavrin *et al.*, arXiv:1006.2103; Phys. Part. Nucl. **46**, 131 (2015); Phys. Rev. D **93**, 073002 (2016)] is presently at the stage of production of the artificial neutrino source ^{51}Cr, and the gallium exposure will start in July and proceed for three months. While aiming specifically at investigating the gallium neutrino anomaly (SAGE and GALLEX experiments) [Abdurashitov *et al.*, Phys. Rev. C **59**, 2246 (1999); **73**, 045805 (2006); Kaether *et al.*, Phys. Lett. B **685**, 47 (2010)], BEST can do more, and it is tempting to estimate its ability to test the sterile neutrino explanation of antineutrino (reactor) anomalies. We observe a moderate sensitivity to the region in model parameter space (sterile neutrino mass and mixing with an active electron neutrino) outlined by the old reactor antineutrino anomaly [Mueller *et al.*, Phys. Rev. C **83**, 054615 (2011); Huber, Phys. Rev. C **84**, 024617 (2011); **85**, 029901 (2012)] and the best fit of DANSS experiment [Alekseev *et al.*, Phys. Lett. B **787**, 56 (2018)], while the Neutrino-4 favorite region [Serebrov *et al.*, Pis'ma Zh. Eksp. Teor. Fiz. **109**, 209 (2019)] falls right in the BEST ballpark. In particular, by analyzing SAGE + GALLEX and Neutrino-4 χ^2 distributions we find that Neutrino-4 results are fully consistent with the gallium anomaly, and the significance of the combined anomaly almost reaches the 4σ level. If the BEST confirms the Neutrino-4 results, the joint analysis will indicate more than the 5σ evidence for the sterile neutrino of eV-scale mass.

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I. INTRODUCTION

Neutrino sector of the Standard Model of particle physics (SM) exhibits more and more puzzling aspects. Apart from neutrino oscillations—the only established phenomenon unambiguously pointing at incompleteness of the SM—there are so-called neutrino anomalies; for reviews see Refs. [1,2]. While the former require SM neutrinos to be massive, the latter ask for a departure from the standard pattern of the three SM (active) neutrinos. The key issue is the new mass scale squared, Δm^2, too high in comparison with the two mass squared differences extracted from the analysis of conventional neutrino oscillations [3]. The attractive solution (though its capability of solving all the anomalies is questionable, e.g., [4]) is oscillations into a new hypothetical light neutrino, sterile with respect to the gauge interaction of the SM.

The anomalies wait for independent checks, which when happening often reveal results suffering from a lack of confidence or even announce new anomalies. Indeed, last year two new experiments—DANSS [5] and Neutrino-4 [6], both dealing with short-baseline neutrino oscillations—have presented their results on searches for $\mathcal{O}(\mathrm{eV})$ sterile neutrinos, which might be responsible for the reactor antineutrino anomaly (RAA) [7,8]. Although the best fit point in the plane (sterile neutrino mass squared $m_s^2 = \Delta m^2$, mixing angle with electron antineutrino θ), referring to the reactor anomaly (actually, to the joint gallium-reactor anomaly; see below), has been excluded at the 2σ level, both experiments claim that other (and different) regions in the model parameter space with eV-scale sterile neutrinos are favored revealing the smallest χ^2 values in the data analyses. The best fit point found by DANSS is [9]

$$\Delta m^2 = 1.4\ \mathrm{eV}^2, \qquad \sin^2 2\theta = 0.05, \tag{1}$$

while the Neutrino-4 collaboration claims 2.8σ evidence for oscillations of electron antineutrinos into sterile antineutrinos with parameters [10]

$$\Delta m^2 = 7.34\ \mathrm{eV}^2, \qquad \sin^2 2\theta = 0.39. \tag{2}$$

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These two claims are new, and though some systematics issues possibly relevant there are discussed in literature [11] (see also RENO hint [12] on time-dependent composition of the reactor fuel, which might resolve RAA), they may be checked directly in the upcoming experiments on neutrino oscillations.

II. GALLIUM ANOMALY

In this paper we investigate BEST prospects in testing the sterile neutrino explanation of these anomalies in the electron antineutrino sector. The main purpose of BEST [13,14] is to check directly the gallium anomaly [15]—deficits of electron neutrino events, observed by SAGE [16,17] and GALLEX [18] experiments in the neutrino capture reaction

$$\nu_e + {}^{71}\mathrm{Ga} \to \mathrm{e}^+ + {}^{71}\mathrm{Ge} \qquad (3)$$

at short distances from neutrino artificial sources. Both experiments have performed two independent measurements with specially designed artificial sources aiming at calibration of the detectors, the main goal of which were measurements of the low-energy tail of the solar neutrino flux. The combined results of the four calibrations can be explained [19] by oscillations into sterile (invisible) neutrinos with best fit parameters [20]

$$\Delta m^2 = 2.5\ \mathrm{eV}^2, \qquad \sin^2 2\theta = 0.3. \qquad (4)$$

Although the gallium anomaly happened in the neutrino sector, within the simplest sterile neutrino paradigm the model parameters (Δm^2, θ) must be the same provided by the CPT symmetry. Actually, the best fit values for the two anomalies are close, and one can combine them in a joint anomaly; see, e.g., [21].

Both experiments, DANSS and Neutrino-4 claim exclusion of the joint anomaly at the 2σ level [9,10], but their sensitivity to each of the two anomalies differ. The reactor antineutrino anomaly itself favors a smaller mixing angle than that of the joint anomaly. It implies a lower signal and higher statistics required for the 2σ exclusion. On the contrary, the gallium anomaly prefers a larger mixing angle, so that Neutrino-4 results (2) are fully consistent with the gallium anomaly. To illustrate this statement we present in Fig. 1 the contour plot of the χ^2 distributions corresponding to both anomalies.[1] One observes that the Neutrino-4 and gallium 1σ contours are widely overlapped, and the best fit point of Neutrino-4 is within the 1σ contour of the gallium anomaly. To further confirm the consistency of the two anomalies, we follow Refs. [14,20] and present in Fig. 2 the likelihood for the joint analysis of the gallium and Neutrino-4 results, assuming one and the same sterile neutrino to be responsible for both anomalies. The significance of the joint anomaly almost reaches 4σ and the best fit point is close to that of Neutrino-4.

[1] χ^2 distribution of the gallium anomaly is calculated in Ref. [20]; we thank the Neutrino-4 collaboration for sharing its χ^2 data analyzed in Ref. [10]. Note that χ^2 contours in our Fig. 1 are a little bit different from the contours on plots of Ref. [10], because the Neutrino-4 collaboration provided us with the updated χ^2 distribution corrected for the systematics used in the concluding part of the paper [10] to estimate the significance of the Neutrino-4 anomaly.

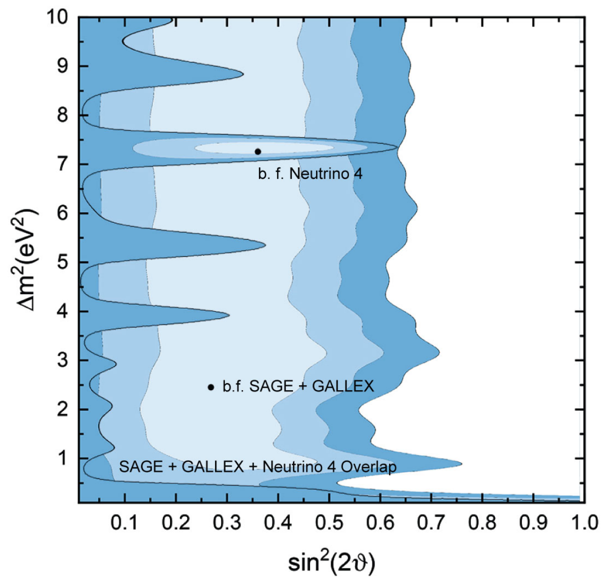

FIG. 1. Overlap of χ^2 contours corresponding to the gallium anomaly and Neutrino-4 results. Colors indicate regions of 1σ, 2σ, and 3σ confidence levels (C.L.). Dots refer to the best fit points (2) and (4).

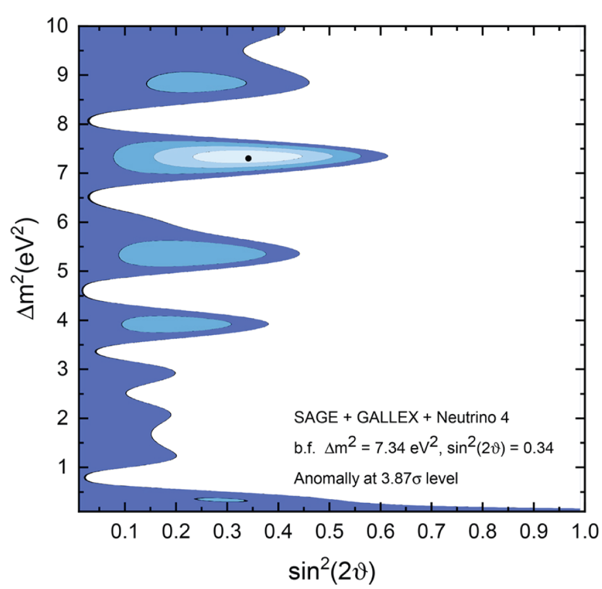

FIG. 2. Regions favored by the combined gallium and Neutrino-4 anomaly at 1-4σ C.L.

III. BEST PRESENT STATUS AND PROSPECTS

To check the gallium anomaly BEST will use the artificial neutrino source ^{51}Cr of 3 MCi to be placed in the center of a spherical vessel filled with a liquid gallium metal target and placed, in turn, in the middle of a cylindrical vessel also filled with a gallium metal target [22]. Thus, the gallium target in both vessels will be exposed to neutrino flux, and because of the reaction (3) the ^{71}Ge atoms will appear via neutrino capture. Then these atoms will be extracted and counted for each gallium target providing direct measurements of the electron neutrino flux averaged over each gallium target volume. The activity of the source will be measured by calorimetry [23] and other methods [24] with accuracy exceeding 1%. Since the neutrino capture rate is the same in both gallium targets, the extractions from both vessels will be used independently to measure the neutrino flux. If the gallium anomaly is really the first evidence for sterile neutrinos, BEST will observe deficits of events (3) in each vessel; the particular numbers depend on the sterile neutrino parameters. The BEST geometry is chosen in order to optimize its sensitivity and make it the highest for the model parameters close to the best fit point of the gallium anomaly (4).

At the first stages of the experiment the vessel for gallium has been constructed and the techniques of filling it with gallium and emptying it have been developed. The gallium has been exposed to the solar neutrinos, and the emerged germanium nuclei have been extracted following the same procedure that will be used for BEST, revealing results fully consistent with predictions of solar neutrino physics. Meanwhile, two independent methods of high-precision measurement of the power of the BEST neutrino artificial source—^{51}Cr of 3 MCi—have been developed [23,24].

The high-power artificial source is the most expensive part of BEST, and the experiment has been approved and received the full financial support only a year and a half ago. Since then several key milestones of the project have been passed. Presently the chromium source is irradiating at the SM-3 reactor in Dimitrovgrad to reach the required intensity. The procedure will be completed by July and the source will be transported to the Baksan Neutrino Observatory of INR RAS. There it will be placed inside the specially designed vessel and radiate gallium for three months. During this period there will be several extractions of germanium nuclei, which are produced in the process (3). The expected sensitivity to the sterile neutrino model explaining the gallium anomaly has been estimated in Ref. [14] and further refined in Ref. [20].

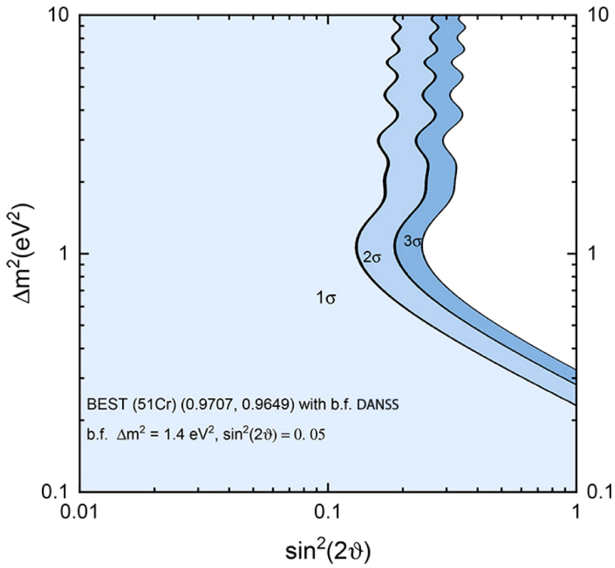

FIG. 3. Parameter space region to be favored by future BEST results at 1-3σ C.L., if it confirms the DANSS best fit (1).

IV. TESTING THE RECENT ANOMALIES AT BEST

Given the optimization based on the gallium anomaly best fit (4) discussed above, BEST exhibits higher sensitivity to the Neutrino-4 favored region (2) than to that of DANSS (1) or that of the original reactor antineutrino anomaly, of which the best fit value (in the fixed flux case [21,25]) is

$$\Delta m^2 = 1.7\ \mathrm{eV}^2, \qquad \sin^2 2\theta = 0.12. \tag{5}$$

To illustrate the BEST abilities we present in Figs. 3 and 4 the regions to be preferred by BEST should its future results confirm the DANSS and reactor anomaly best fit values, respectively. One observes that BEST results could contribute to the significance of corresponding anomalies,

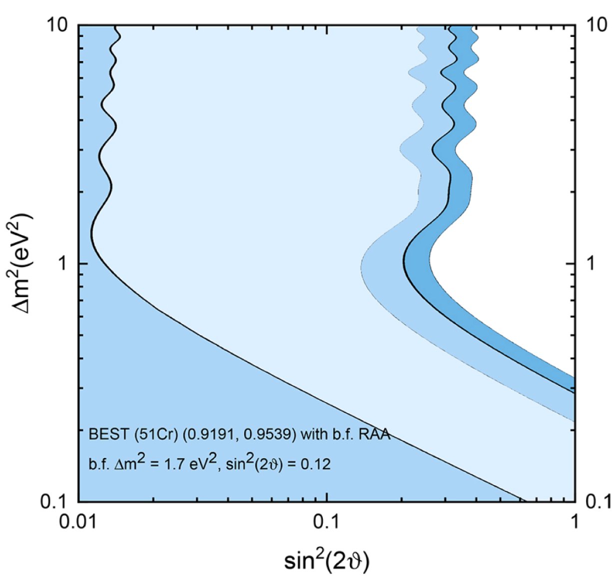

FIG. 4. The region in model parameter space to be favored by future BEST results at 1-3σ C.L. if it confirms the RAA (5).

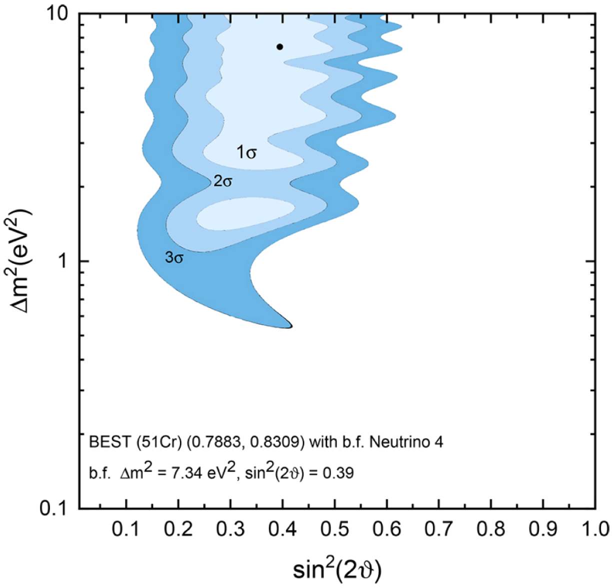

FIG. 5. The region in sterile neutrino model parameter space to be favored by future BEST results at 1-3σ CL if it confirms the Neutrino-4 anomaly (2).

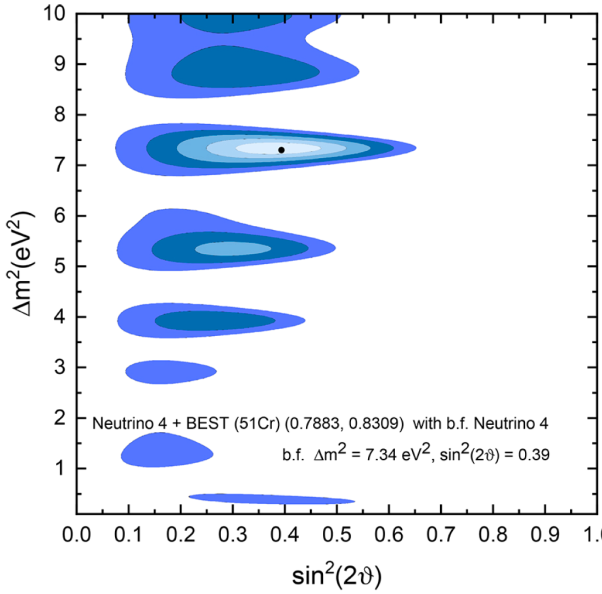

FIG. 6. The region of sterile neutrino parameters to be favored at 1-5σ CL by joint analysis of Neutrino-4 and future BEST results if the latter confirms the former (2).

but rather modestly. In contrast, if future BEST results confirm the Neutrino-4 claim, it will imply stronger than 3σ confirmation; see Fig. 5. In that case, if combined with Neutrino-4 data, the joint anomaly will exceed the 5σ level (see Fig. 6) typically accepted as a discovery condition in particle physics.

So far we have considered the BEST ability in confirming the anomalies and hence discovering the new physics. This is the most attractive situation; however, it is not guaranteed, and all the anomalies can disappear with results of upcoming experiments. In particular, the analysis of Ref. [20] ensures that if BEST confirms the standard three-neutrino oscillation pattern (see Fig. 4 there), the Neutrino-4 anomaly will be excluded at more than the 3σ level. As BEST sensitivities to the reactor anomaly and DANSS best fit point are worse, the corresponding exclusion power there is too low to change their status.

V. CONCLUSIONS

To summarize, we analyze the sensitivity of BEST to the regions in the sterile neutrino model parameter space capable of explaining anomalies in electron antineutrino oscillation experiments: the (old) reactor antineutrino anomaly and the recent results of DANSS and Neutrino-4 experiments.

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