

Bulk neutrinos as an alternative cause of the gallium and reactor anti-neutrino anomaliesP. A. N. Machado,^{1,2,*} H. Nunokawa,^{3,†} F. A. Pereira dos Santos,^{3,‡} and R. Zukanovich Funchal^{1,§}¹*Instituto de Física, Universidade de São Paulo, C. P. 66.318, 05315-970 São Paulo, Brazil*²*Institut de Physique Théorique, CEA-Saclay, 91191 Gif-sur-Yvette, France*³*Departamento de Física, Pontifícia Universidade Católica do Rio de Janeiro, C. P. 38071, 22452-970, Rio de Janeiro, Brazil*

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We consider an alternative explanation for the deficit of ν_e in Ga solar neutrino calibration experiments and of the $\bar{\nu}_e$ in short-baseline reactor experiments by a model where neutrinos can oscillate into sterile Kaluza-Klein modes that can propagate in compactified submicrometer flat extra dimensions. We have analyzed the results of the gallium radioactive source experiments and 19 reactor experiments with baseline shorter than 100 m, and showed that these data can be fit into this scenario. The values of the lightest neutrino mass and of the size of the largest extra dimension that are compatible with these experiments are mostly not excluded by other neutrino oscillation experiments.

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I. INTRODUCTION

We have been living in exceptional times in neutrino physics. Neutrino mixings and masses have been substantiated by a plethora of oscillation experiments, which favor the standard three flavor mixing scheme. Solar [1] and atmospheric [2] neutrino experiments have established two fairly large mixing angles and two distinct mass squared differences, which today are rather precisely determined by reactor [3] and accelerator experiments [4,5]. Recently T2K [6] has announced that their data provides indication of a nonzero, and perhaps far from negligible, value of θ_{13} , supported also by MINOS [7], opening the auspicious possibility to access CP violation in the leptonic sector by current or near future experiments.

While all the neutrino data mentioned above can be fit very well into the standard picture of the three flavor neutrino scheme, there have been some data [8,9] which are not consistent with such a picture. First, the LSND [8] experiment has observed an excess of $\bar{\nu}_e$ events in the $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ mode, which seemed to be supported by MiniBooNE data [9], indicating the presence of at least one species of the so-called sterile neutrinos. These neutrinos would have to be separated from the active neutrinos by a mass squared difference of $\sim eV^2$. Let us call this the LSND/MiniBooNE anomaly.

Likewise, calibrations of the gallium radiochemical solar neutrino detectors of GALLEX [10] and SAGE [11] experiments performed using intense portable neutrino radioactive sources, ^{51}Cr by GALLEX and SAGE, and ^{37}Ar by SAGE, observed some deficit of ν_e compared to what was expected, giving rise to the so-called *gallium anomaly*. The mean value of the ratios of the measured over predicted rates

is 0.86 ± 0.05 , which is smaller than unity by about 2.7σ [12]. This can also be explained by oscillation into sterile neutrinos with the similar mass squared difference, which explains the LSND/MiniBooNE anomaly.

More recently, a reevaluation of the reactor $\bar{\nu}_e$ flux [13,14], performed in order to prepare for the Double Chooz reactor experiment [15], resulted in an increase in the flux of 3.5%. While this increase has essentially no impact on the results of long baseline experiments such as KamLAND, it induces an average deficit of 5.7% in the observed event rates for short-baseline (<100 m) reactor neutrino experiments leading to the 98.6% CL deviation from unity, which has been referred to as the *reactor antineutrino anomaly* [16].

It was shown in Ref. [16] that these three anomalies can be explained by a phenomenological $3 + 1$ model, where the oscillation scheme involves the three active neutrinos and one additional species of sterile neutrino. In Refs. [17,18] a global fit of the short-baseline experiments (but without Ga data) with sterile neutrinos was performed, and it was concluded that data can be fitted significantly better in a $3 + 2$ model.

In the interim, however, the LSND/MiniBooNE anomaly has diminished substantially. A more recent MiniBooNE result, based on the 8.58×10^{20} POT, reduced the significance of the $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ excess to 0.84σ [19] and very recently the HARP-CDP Group [20] presented new data on pion production that also decreased the significance of the LSND excess from 3.8 to 2.9σ .

In this paper, we will show that the two anomalies seen in the disappearance channels, the gallium and the anti-neutrino reactor ones, can be accommodated in a scenario where three right-handed neutrinos propagate in a higher dimensional bulk, including a large compactified flat extra dimension [21], and all standard model particles are confined to a 4-dimensional brane. The 3 bulk fermions have Yukawa coupling with the Higgs and the brane neutrinos leading to small Dirac neutrino masses and mixings

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among active species and sterile Kaluza-Klein modes [22–27].

It is important to emphasize that the model presented here is significantly different from the phenomenological models studied in Refs. [16–18]. In general, a $3 + n$ phenomenological model assumes that the three active neutrinos can mix with n sterile species which implies that, in addition to the $2 + n$ mass squared differences, the $(3 + n)(2 + n)/2$ mixing angles, and $(2 + n)(1 + n)/2$ phases are free parameters relevant for oscillation physics. Therefore, the number of relevant parameters for the $3 + n$ model is significantly larger than that of the standard three flavor scheme. We, however, note that in the phenomenological approach, usually, the numbers of free parameters used in the fit are reduced to simplify the analysis in these models, as done in Refs. [16–18].

On the other hand, besides providing an explanation for the smallness of neutrino masses [22], the free parameters of the LED model described here that can have some impact on oscillation physics are the 3 mixing angles, one CP phase, the radius of the largest extra dimension and the neutrino mass scale. The mixing between the active neutrinos and the KK sterile modes is completely determined by these parameters. So, despite being (innately) conceptually more elaborated than the phenomenological $3 + n$ models, the LED model considered in this work is intrinsically much more constrained as a model, once it involves less free parameters [28].

This alternative explanation is consistent with the results of the current terrestrial experiments such as CHOOZ [29], KamLAND [3] and MINOS [5] limits and seem to be consistent with solar [1] and atmospheric [2] oscillation as discussed in Ref. [30]. However, the $\bar{\nu}_e$ excess observed in the LSND and MiniBooNE experiments can not be explained by the scenario addressed here, and therefore we do not consider them in this work.

II. NEUTRINO OSCILLATIONS WITH A LARGE EXTRA DIMENSION

The large extra dimension (LED) picture we will consider here is the one described in Refs. [27,30]. There the 3 standard model (SM) left-handed flavor neutrinos fields ν_α ($\alpha = e, \mu, \tau$), as well as all the other SM fields, are confined to propagate in a 4-dimensional brane, while 3 SM singlet fermion fields can propagate in a higher dimensional bulk, with at least two compactified extra dimensions. To retain simplicity, we will assume that one of these extra dimensions, compactified on a circle of radius $a \lesssim 1 \mu\text{m}$ [30], is, however, much larger than the size of the others, so that in practice a 5-dimensional treatment is enough.

The 3 bulk fermions have Yukawa couplings with the SM Higgs and the brane neutrinos, ultimately leading to flavor oscillations driven by Dirac masses, m_i ($i = 1, 2$ and 3), and

Kaluza-Klein (KK) masses m_n^{KK} ($n = 1, 2, \dots$), and mixings among active species and sterile modes. In this case the ν_e (same as $\bar{\nu}_e$ due to CPT conservation) survival probability in vacuum can be written as [27,30]

$$P(\nu_e \rightarrow \nu_e; L, E) = |\mathcal{A}_{\nu_e \rightarrow \nu_e}(L, E)|^2, \quad (1)$$

where the amplitude is given by

$$\mathcal{A}_{\nu_e \rightarrow \nu_e}(L, E) = \sum_{i=1}^3 |U_{ei}|^2 A_i, \quad (2)$$

where A_i is given by, assuming $m_i a \ll 1$ and ignoring the terms of order $(m_i a)^3$ and higher in the amplitude as well as $(m_i a)^2$ and higher in the phase,

$$A_i \approx \left(1 - \frac{\pi^2}{6} m_i^2 a^2\right)^2 \exp\left(i \frac{m_i^2 L}{2E}\right) + \sum_{n=1}^{\infty} 2 \left(\frac{m_i}{m_n^{\text{KK}}}\right)^2 \times \exp\left[i \frac{(2m_i^2 + m_n^{\text{KK}2})L}{2E}\right]. \quad (3)$$

Here U_{ei} are the elements of the first row of the usual Maki-Sakata-Nakagawa neutrino mixing matrix (we use the standard parameterization found in Ref. [31]), E is the neutrino energy, L is the baseline distance, $m_n^{\text{KK}} = n/a$ is the mass of the n -th KK mode.

This survival probability depends on the neutrino mass hierarchy, for normal hierarchy (NH) we have $m_3 > m_2 > m_1 = m_0$ and inverted hierarchy (IH) we have $m_2 > m_1 > m_3 = m_0$. Clearly, as m_0 increases the differences between the hierarchies fade away and the masses become degenerate. So besides the usual oscillation parameters $\Delta m_{32}^2 = |m_3^2 - m_2^2|$, $\Delta m_{21}^2 = m_2^2 - m_1^2$, $\sin^2 \theta_{12}$, $\sin^2 \theta_{13}$, which are basically fixed by the data from the current oscillation experiments, LED oscillations will be also driven by a and m_0 which also have been constrained by experimental data [27,30]. Throughout this work, even in the presence of LED, we consider, to a good approximation, the following true (input) values of the standard oscillation parameters determined by the three flavor analysis of experimental data: $\Delta m_{21}^2 = 7.6 \times 10^{-5} \text{ eV}^2$, $\sin^2 2\theta_{12} = 0.31$, $|\Delta m_{31}^2| = 2.4 \times 10^{-3} \text{ eV}^2$.

If $a \lesssim 1 \mu\text{m}$, the LED effect at short baselines is simply to promote $\nu_e \rightarrow \nu_n^{\text{KK}}$, converting part of the ν_e signal into KK modes, producing a nearly energy independent depletion of the ν_e rates, and the same applies to antineutrinos. To illustrate this we show in Fig. 1 the survival probability for a few sets of LED parameters as well as the radioactive source test experiments and reactor rates.

How can one understand these results? One can easily show that for the short-baseline experiments, to leading order, the averaged surviving probability with the LED effect is

$$\langle P(\nu_e \rightarrow \nu_e) \rangle \approx \left[\sum_{i=1}^3 |U_{ei}|^2 \left(1 - \frac{\pi^2 m_i^2 a^2}{6}\right)^2 \right]^2. \quad (4)$$

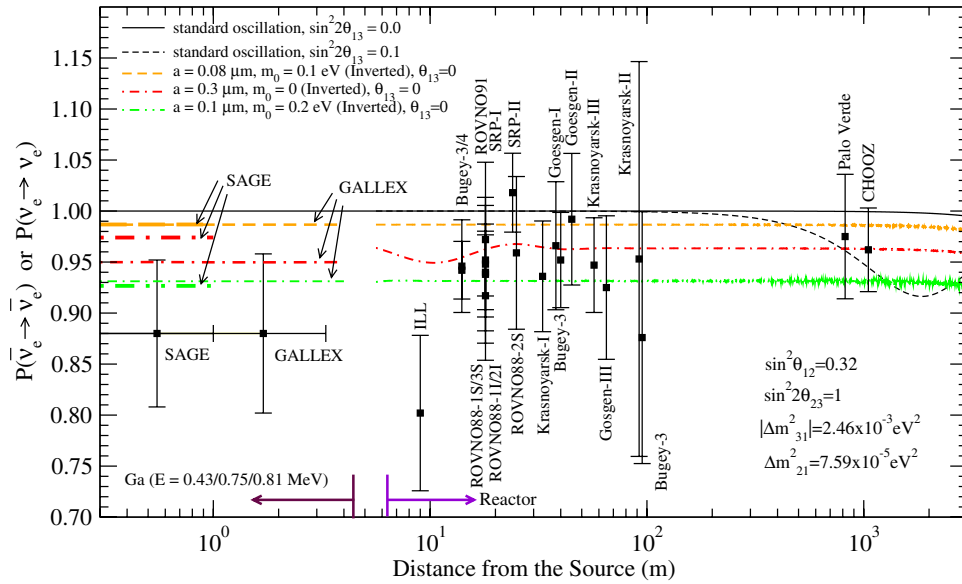


FIG. 1 (color online). Survival probability as a function of the distance from the ν_e ($\bar{\nu}_e$) source averaged over the detector position (reactor energy spectrum). To illustrate how LED, in principle, can explain the short-baseline anomalies we show this probability for (a) standard oscillation with $\sin^2 2\theta_{13} = 0.0$ and $\sin^2 2\theta_{13} = 0.1$ and (b) LED for IH with $\theta_{13} = 0$ and some values of the LED parameters: $a = 0.3 \mu\text{m}$, $m_0 = 0$, $a = 1.0 \mu\text{m}$, $m_0 = 0.2 \text{eV}$, $a = 0.08 \mu\text{m}$, $m_0 = 0.1 \text{eV}$. We also show the average experimental deficits for the source test experiments GALLEX and SAGE, as well as for the reactor experiments ILL, Bugey-3, Bugey-3/4, ROVNO88-1S/3S, ROVNO88-1I/2I, ROVNO88-2S, SRP-I, SRP-II, Gosgen-I, Gosgen-II, Gosgen-III, Krasnoyarsk-I, Krasnoyarsk-II, Krasnoyarsk-III, Palo Verde, and CHOOZ where the reactor data were taken from the Table II of Ref. [16].

Therefore, if $a = 0.3 \mu\text{m} \approx 3/2 \text{eV}^{-1}$, $m_3 = m_0 = 0$, $m_1 \approx m_2 \sim 0.05 \text{eV}$, or if $a = 0.1 \mu\text{m} \approx 1/2 \text{eV}^{-1}$, $m_3 = m_0 = 0.2 \text{eV} \approx m_1 \approx m_2$, or if $a = 0.08 \mu\text{m} \approx 2/5 \text{eV}^{-1}$, $m_3 = m_0 = 0.1 \text{eV} \approx m_1 \approx m_2$, the survival probability can be estimated as $\sim 1 - 2\pi^2 a^2 m_2^2 / 3$, given, respectively, $\sim 0.96, 0.93, 0.99$.

III. ANALYSIS RESULTS

A. Gallium radioactive source experiments

Let us first look at the gallium anomaly. The radiochemical solar neutrino experiments GALLEX and SAGE have been calibrated with monoenergetic ν_e 's from intense radioactive sources, which are captured by the reaction,

$$\nu_e + {}^{71}\text{Ga} \rightarrow {}^{71}\text{Ge} + e^- \tag{5}$$

GALLEX collaboration published the results of their measurements with two ${}^{51}\text{Cr}$ sources [10]. SAGE collaboration performed similar measurements with ${}^{51}\text{Cr}$ and also with ${}^{37}\text{Ar}$ sources [11].

They presented their results in terms of a ratio, R , of the measured ${}^{71}\text{Ge}$ event rate over the predicted one using the predicted cross section for the reaction (5) estimated in Ref. [32], including errors. All the measured ratios are below unity,

$$R_{\text{Cr1}}^{\text{G}} = 0.95 \pm 0.11, \tag{6}$$

$$R_{\text{Cr2}}^{\text{G}} = 0.81 \pm 0.11, \tag{7}$$

for GALLEX [10] we used the values based on the pulse shape analysis obtained by Kaether *et al.* in Ref. [10] and

$$R_{\text{Cr}}^{\text{S}} = 0.95 \pm 0.12, \tag{8}$$

$$R_{\text{Ar}}^{\text{S}} = 0.79 \pm 0.09, \tag{9}$$

for SAGE [11].

An analysis of these results in terms of oscillation of ν_e into sterile neutrinos was performed in Refs. [12,33].

We have done an analysis similar to the one described in Ref. [33]. Table I shows the data needed to perform our calculation. We have computed the theoretical value of the ratio R for LED as

TABLE I. For the GALLEX and SAGE source experiments we give the ν_e energy (E) of the primary ν_e line emitted by the source, the radius (r) and height (h) of the cylindrical detector volumes and the position of the sources in terms of height from the base of the detectors. The sources were placed along the axes of the detectors.

	GALLEX		SAGE	
	Cr1	Cr2	Cr	Ar
E (keV)	750		750	811
r (m)	1.9		0.7	
h (m)	5.0		1.47	
source position (m)	2.7	2.38	0.72	

$$R = \frac{\int dVL^{-2} P(\nu_e \rightarrow \nu_e; L, E)}{\int dVL^{-2}} \quad (10)$$

by Monte Carlo integration. In fact, there are four different ν_e lines emitted by the ^{51}Cr source, two with energy around 750 keV and cross section $\sim 61 \times 10^{-46} \text{ cm}^2$ (90%) and two with energy around 430 keV and cross section $\sim 27 \times 10^{-46} \text{ cm}^2$ (10%) and two different ν_e lines emitted by the ^{37}Ar source, both with energy around 810 keV. We have verified that taking into account these different contributions in the calculation of R as in Ref. [12] does not affect our final result, so for the purpose of this paper it is enough to use Eq. (10).

We have performed a χ^2 analysis of the data and found a region allowed for the LED parameters m_0 and a that fit well the for data points, $\chi^2_{\text{min}}/\text{dof} = 1.81/2 = 0.905$. In the left panels of Fig. 2, the allowed regions are shown for NH (upper panel) and IH (lower panel). For the purpose of comparison we also indicated in all the panels, by a solid curve, the region excluded by KamLAND, CHOOZ and MINOS obtained in Ref. [30]. We note that the 1σ allowed region is basically excluded by other experiments but there are still large 2 and 3σ regions which are not in conflict with them. In fact, from Fig. 1 one can expect that there could be some ‘‘tension’’ between the Ga and reactor data

as the former prefer somewhat stronger reduction than the latter.

B. Short-baseline reactor neutrino experiments

Using the new reactor antineutrino flux calculations [13,14] the ratio between the number of $\bar{\nu}_e$ observed and theoretically predicted for all short-baseline reactor experiments has decreased by 5.7% [16].

We have simulated the expected rates of the following 19 reactor experiments with baselines shorter than 100 m: Bugey-3-I/III [34] at 15, 40 and 90 m, of Bugey-4 [35] at 15 m, of ILL [36] at 9 m, of Gosgen-I/III [37] at 38, 45 and 65 m, of Savannah River (SRP-I/II) [38] at 18 and 24 m, of Krasnoyarsk-I/III [39] at 33, 92 and 57 m, ROVNO88-1I/2I/1S/3S [40] at 18 m, ROVNO88-2S [40] at 25 m and ROVNO91 [41] at 18 m.

Our simulation follows closely the one described in Ref. [16]. We use the isotopic compositions and new rates provide in Table II of Ref. [16], as well as the χ^2 function with the covariance matrix defined in this reference. Regarding the covariance matrix, it is important to highlight that each element should be multiplied by the respective rate. In other words, following the notation of [16], each element of the covariance matrix W is defined as $W_{ij} = \sigma_{ij}^2 R_i R_j$, where σ_{ij}^2 is the correlated error

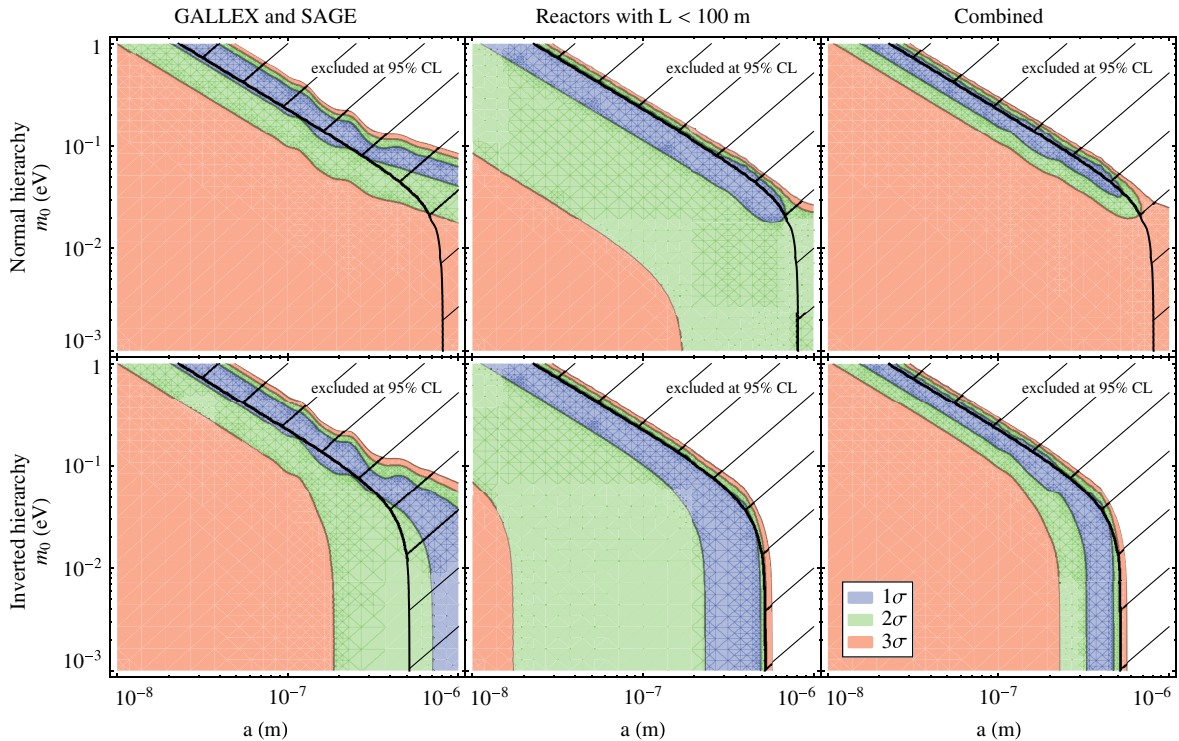


FIG. 2 (color online). Regions in the plane m_0 versus a at 68%, 95%, and 99.73% CL (that is 1, 2, and 3σ) allowed by GALLEX and SAGE source calibration experiments (left panels), by short-baseline reactor data (middle panels) and by the combined case of these two data set (left panels). For each case, the upper (lower) panel correspond to the normal (inverted) hierarchy. The hatched areas correspond to the 95% CL limits from terrestrial oscillation experiments derived in Ref. [30].

between experiments i and j when $i \neq j$ or simply the corresponding experiment error for diagonal elements, and R_i is the ratio of observed over expected number of events of the experiment i . To obtain the theoretical rates with LED, we used the experimental results available in Refs. [34–41] and the parameterization given in [16] to calculate the expected reactor fluxes. We implemented all experiments using a modified version of GLoBES [42].

We have fitted the new rates in the LED scenario and obtained the allowed regions for the LED parameters m_0 and a . In the middle panels of Fig. 2 we show these regions for NH (upper panel) and IH (lower panel). We observe that these regions are more compatible with the limits coming from other oscillation experiments [30], indicated by the black solid curve, than the ones obtained by Ga data shown in the left panels of Fig. 2.

C. Combined analysis

Finally, we show the results of the combined LED analysis for GALLEX and SAGE source experiments with the one for the 19 short-baseline reactor experiments. In the right panels of Fig. 2 we show the allowed regions for NH (upper panel) and IH (lower panel) in the plane of m_0 and a obtained by combining Ga source experiment and short-baseline reactor experiments. We found that the combined data favor the nonzero value of the large extra dimension, 2.9σ away from $a = 0$.

We have further combined results of these Ga source and short-baseline reactor data and the data coming from KamLAND, CHOOZ, and MINOS previously considered in Ref. [30] but we do not show the plot here as it is quite similar to what have been shown in the right panels of Fig. 2. The reason is that the region favored by gallium and reactor antineutrino anomalies and the region excluded by KamLAND, CHOOZ and MINOS overlap scarcely.

IV. DISCUSSIONS AND CONCLUSIONS

Current neutrino data exhibit three anomalies, one in the appearance mode, $\bar{\nu}_e$ excess in LSND [8] and MiniBooNE [9] experiments, the other two are deficit of ν_e in the gallium solar neutrino calibration experiments [10,11] and of $\bar{\nu}_e$ in the short-baseline (<100 m) reactor experiments [16]. Possible solutions to these problems, involving oscillation into one or two species of sterile neutrinos whose mass squared differences are separated from the active ones by $\sim eV^2$, have been proposed.

In this work we show that the two of these anomalies in the disappearance mode can be explained by an alternative solution, oscillation of ν_e and $\bar{\nu}_e$ into sterile Kaluza-Klein neutrinos which are present in a model with large extra dimensions with a dimension size of $\lesssim 0.6 \mu\text{m}$, and compatible with the limits coming from other oscillation experiments analyzed in Ref. [30].

Let us make some comments on LED limits coming from other sources/considerations besides KK bulk neutrinos. First, cosmological and astrophysical bounds on LED (or equivalently on the fundamental scale of gravity) due to the over production and/or decays of KK gravitons into SM particles in various cosmological/astrophysical environments give, in general, much stronger bounds than the ones coming from laboratory experiments [43–47]. However, since these bounds are not completely model independent and not coming directly from the presence of the KK neutrinos, we do not try to make a direct comparison here.

Instead, we prefer to quote some cosmological limits coming directly from the presence of the KK neutrinos obtained in Refs. [48,49]. In Ref. [48] for the case where the “normalcy” temperature of the universe (considered as the temperature at which the universe should be free from the KK modes for graviton production, see the last reference in [21]) was assumed to be $\lesssim 1 \text{ GeV}$, for $\delta = 4$ (δ being the number of large extra dimensions of equal size), by requiring that neutrinos should not contribute too much to the energy density of the universe, a size larger than $\sim 1 \mu\text{m}$ for m_i larger than 0.01 eV is excluded (for $\delta = 5, 6$ the bounds become stronger, see Fig. 2 of [48]). This may seem to exclude our solution, but we can not make a direct comparison since we assumed here that only one, the largest extra dimension (the other dimensions having negligible size), can contribute to alter significantly the oscillation probability.

On the other hand, a complementary analysis to Ref. [48] was performed in Ref. [49] where a bound on the size of the largest extra dimension was derived such that the KK modes would not cause any conflict between the successful theoretical predictions of the Big Bang Nucleosynthesis (BBN) and its observations. Since in this case it was assumed that only a single KK tower would contribute to modify BBN, we can make a direct comparison. From Fig. 1 of Ref. [49], we observe that the typical solution we found, $a \sim a \text{ few} \times 0.1 \mu\text{m}$ and $m_i \sim O(0.1) \text{ eV}$ is still allowed.

We note that the $\bar{\nu}_e$ excess observed in the LSND and MiniBooNE experiments cannot be explained by the simple LED scenario we consider in this work. In order to do that this scenario would have to be extended (see Ref. [27]), however the LSND/MiniBooNE anomaly is becoming much weaker with new data.

While the future MINOS and Double CHOOZ data can improve somewhat the limits in the small m_0 parameter region [50], it seems not easy to exclude or confirm the LED solution discussed in this work. This also seems to apply to the sterile neutrino explanations discussed in Refs. [16–18]. In fact, as far as the gallium and reactor antineutrino anomalies are concerned, behavior of these two solutions are similar (as both of these solutions exhibit rapid oscillations) so that it would not be so easy to distinguish them.

Possibly, a large liquid scintillator detector with very low background such as KamLAND [3] using a PBq scale radioactive source deployed in its center, capable of very good vertex reconstruction, as discussed in Ref. [16,51], could allow us to observe the rapid oscillation patterns which may help in identifying the solution to the gallium and reactor antineutrino anomalies. See also Ref. [52].

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