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The reactor antineutrino anomaly and low energy threshold neutrino experiments

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ABSTRACT

Short distance reactor antineutrino experiments measure an antineutrino spectrum a few percent lower than expected from theoretical predictions. In this work we study the potential of low energy threshold reactor experiments in the context of a light sterile neutrino signal. We discuss the perspectives of the recently detected coherent elastic neutrino–nucleus scattering in future reactor antineutrino experiments. We find that the expectations to improve the current constraints on the mixing with sterile neutrinos are promising. We also analyze the measurements of antineutrino scattering off electrons from short distance reactor experiments. In this case, the statistics is not competitive with inverse beta decay experiments, although future experiments might play a role when compare it with the Gallium anomaly.

1. Introduction

Neutrino physics is already in the precision physics era; with recent Nobel prize awarded in 2015 and with most of the Standard Model parameters already measured with good accuracy [1–3]. Future neutrino experiments will try to improve the determination of these parameters, especially the neutrino CP violating phase [4]. Besides oscillations, there is also a complete program of neutrino experiments aiming to improve the measurements of neutrino cross sections [5,6].

Historically, reactor neutrino experiments have been a powerful tool in the measurement of neutrino electron scattering [7]. Recently, several experiments have measured this process with an increased precision [8–11] and it is expected that new results will be reported in the near future, for instance by the GEMMA experiment [12]. Despite the small cross section, neutrino electron scattering data have given interesting results on neutrino properties, such as neutrino magnetic moments [13], as well as on the value of the weak mixing angle at low energies [14].

Regarding inverse beta decay (IBD) experiments, besides the successful measurements of the standard oscillation parameters, both for long [15,16] and for short baselines [17–19], there is also a complete program to unambiguously discover or exclude sterile neutrinos in the near future. Some of these experiments are underway and others will start data taking soon [20–22]. The DANNS experiment [23] has already presented preliminary results. On the other hand, recent results from the NEOS experiment already exclude part of the previously allowed region in the most recent $3+1$ sterile neutrino data fit [24].

Also in the low energy threshold regime, there is the coherent elastic neutrino nucleus scattering (CENNS), that was studied for the first time in the seventies [25] and has finally been observed [26]. A large number of proposals are also looking for this signal, and there will be several measurements of the neutrino cross sections with this reaction in the future. As it has been proved by the COHERENT Collaboration [26], CENNS is a very promising process for low energy neutrino physics. Several works have pointed out its impact in testing non-standard interactions [27–32], neutrino magnetic moment, or the weak mixing angle [33–35].

Recently, the sensitivity of CENNS to a sterile neutrino has been studied for the case of the Texono and the COHERENT proposals [36]. Since the revaluation of the reactor antineutrino energy spectrum [37], the possibility of an additional sterile neutrino [38] has been under scrutiny. Most of the evidence for this anomaly comes from short baseline reactor experiments using IBD and from the so-called Gallium anomaly [39,40]. In this work we also study the case of a light sterile neutrino, considering a wider set of experimental proposals that plan to use CENNS. We focus in the case

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of reactor antineutrino fluxes. In this sense, our work compares different proposals that use a similar antineutrino flux and discuss the advantages and complementarities of these future experiments.

At the same time, we also discuss in more detail the case of a different prescription for the reactor antineutrino flux as a solution to the so called reactor anomaly. After the recent evaluation of the antineutrino spectrum by Daya Bay [41], the need for a better understanding of the spectrum has been pointed out. Moreover, the possibility that the reactor anomaly can be solved by a revaluation of the antineutrino flux has also been considered [42]. Since the data in the reactor signal for sterile neutrinos come from IBD experiments, it will be interesting to consider alternative detection technologies as a complementary test to this anomaly. For this reason we study here the current data from neutrino electron scattering, as well as the prospects of CENNS.

2. Antineutrino electron scattering measurement

In this section we concentrate our study in experiments that use the electron antineutrino scattering off electrons as the detection process. For this purpose, we have reanalyzed the experimental results, using the current prescription for the reactor antineutrino flux [37], to obtain a restriction on the mixing parameters of a sterile neutrino. Following this approach, the effective survival probability for short baseline antineutrino experiments in the $3+1$ mixing scheme[1] can be written as [48]

$$P^{\mathrm{SBL}}_{\bar{\nu}_e\to\bar{\nu}_e} = \sin^2 2\theta_{ee} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right), \tag{1}$$

where

$$\sin^2 2\theta_{ee} = 4|U_{e4}|^2(1-|U_{e4}|^2). \tag{2}$$

The expected number of events, in the presence of a fourth, sterile, neutrino state, will be given in this case as

$$N_i = n_e \Delta t \int \int_{T_i}^{T_{i+1}} \int \lambda(E_\nu) P^{\mathrm{SBL}}_{\nu_\alpha\to\nu_\alpha} \frac{d\sigma}{dT} R(T,T') dT' dT dE, \tag{3}$$

where $\lambda(E_\nu)$ stands for the antineutrino spectrum; for energies above 2 MeV, this spectrum has been taken according to Ref. [37]; on the other hand, if we need to include energies bellow 2 MeV, we have included the spectrum computed in Ref. [49]. $R(T,T')$ is the resolution function for the given experiment, $P^{\mathrm{SBL}}_{\nu_\alpha\to\nu_\alpha}$ is the effective survival probability as given in Eq. (1), and $\frac{d\sigma}{dT}$ is the differential cross section for the antineutrino scattering off electrons, given as [50]

$$\frac{d\sigma}{dT} = \frac{2G_F^2 m_e}{\pi}\left[g_R^2 + g_L^2(1-\frac{T}{E_\nu})^2 - g_L g_R m_e \frac{T}{E_\nu^2}\right], \tag{4}$$

where m_e stands for the electron mass and G_F is the Fermi constant. In this expression, $g_L = 1/2 + \sin^2\theta_W$ and $g_R = \sin^2\theta_W$ are the usual Standard Model couplings.

Several experiments using neutrino electron scattering as detection reaction have been performed along the years. Some of them have searched for a non-zero neutrino magnetic moment [51]. The experiments for our analysis will be TEXONO, MUNU, Rovno and Krasnoyarsk. The most recent experimental result has been given by the TEXONO Collaboration [11], that has reported the measurement of ten bins with an electron recoil energy between 3 and 8 MeV. The energy resolution for this experiment was $\sigma(T) = 0.0325\sqrt{T}$ [52]. A previous experiment, with a lower threshold, was performed by the MUNU Collaboration [53]. In this case, the error in the electron recoil energy was considered to be $\sigma(T) = 0.08\ \mathrm{T}^{0.7}$ [54]. We also considered the Rovno [9] and Krasnoyarsk [8] results. For these experiments, the fuel proportions, as well as the electron recoil energy window, are shown in Table 1.

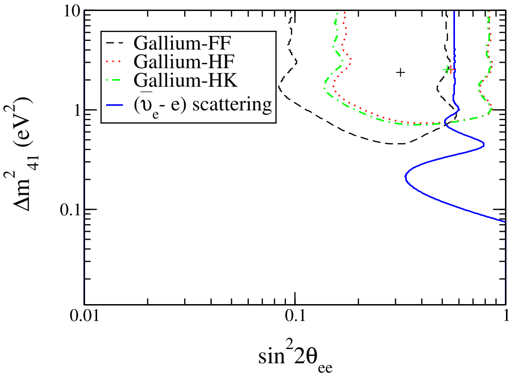

Fig. 1. Restrictions for a sterile neutrino from a combined analysis of neutrino electron scattering from reactor experiments at 90% C L (blue solid line). We also show for comparison, the results for the Gallium anomaly [55] in the three cases discussed in the text. The best-fit values are indicated by a cross.

We have performed a goodness of fit analysis for the experiments quoted above. After performing the combined fit using the four reactor experiments, we have obtained the restriction for the sterile oscillation parameters, $\sin^2 2\theta_{ee}$ and Δm^2_{41}, as shown in Fig. 1. We also show in this figure the allowed regions for the Gallium anomaly [39,40]. We have followed the procedure described by Giunti et al. [40,55], with the only difference of including in our analysis the updated results for the Gamow–Teller transitions reported by Frekers et al. [56] (FF). This result is shown as a dash line in Fig. 1. This recent measurement has also been considered for the case of the future experiment BEST [57]. As it is possible to notice, the current resolution from electron antineutrino scattering off electrons has no overlap with this region. Therefore, the constraint obtained here would be of interest only if one considers other measurements of the Gamow–Teller transitions, such as that of in the (p,n) experiment of Krofcheck et al. [58] (HK, dash-dotted line) or the shell model of Haxton [59] (HF, dotted line), also considered in the Ref. [55]. It would be expected that new measurements of the antineutrino–electron scattering could be more restrictive, as in the case of the proposed GEMMA updated experiment [12]. Still, despite the increased interest in solving the Gallium anomaly [57], current global analysis on the sterile signal [60,61] give a region that is in tension with the large value of $\sin^2 2\theta_{ee}$ obtained from the Gallium data. For that reason we discuss in the next section the case of coherent elastic neutrino nucleus scattering as a promising technique to give complementary information to that coming from inverse beta decay experiments.

3. Perspectives for coherent neutrino nucleus scattering in reactor experiments

The CENNS is another interesting process to explore physics beyond the Standard Model. This interaction was proposed more than four decades ago within the SM context [25,62]. Different Collaborations and experimental proposals have considered the possibility of detecting the coherent neutrino–nucleus scattering [63–66]. Recently the COHERENT Collaboration has achieved the first detection

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[1] A different oscillation channel to a sterile neutrino would be that of a $\nu_\mu \to \nu_s$ transition, as hinted by the LSND [43] and MiniBooNE [44] Collaborations. Since we focus in a different channel, for this case we refer the reader to the limits reported in Refs. [45–47].

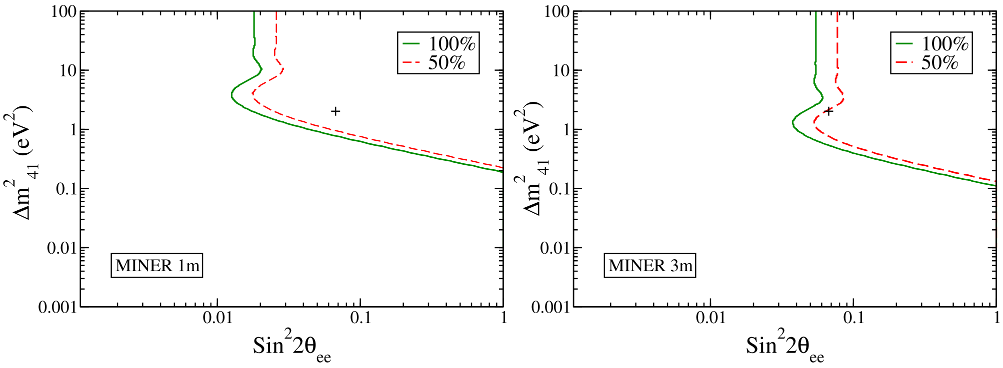

Fig. 2. Exclusion regions for the MINER experiment. The left (right) panel corresponds to a baseline of 1 (3) m. The solid (green) line is for a detector with 100% efficiency and the dashed (red) line is for a 50% efficiency. The current best fit point for the sterile analysis is shown as a reference.

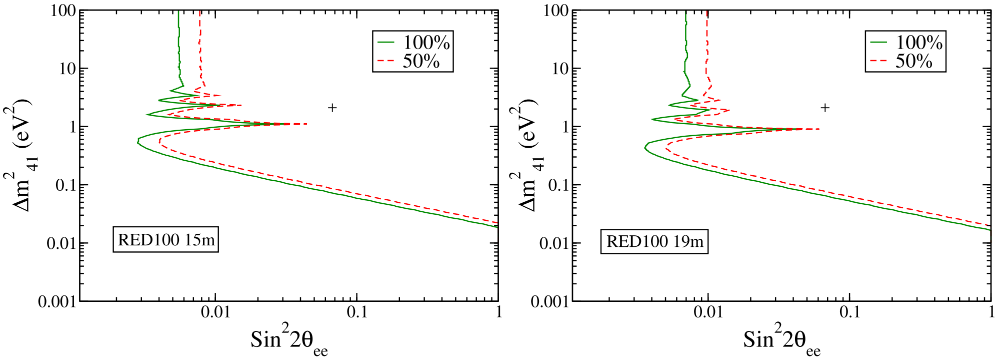

Fig. 3. Exclusion regions for the RED100 proposal. The left (right) panel shows the case of a baseline of 15 (19) m. The solid (green) line correspond to a detector with 100% efficiency and the dashed (red) lines a 50% efficiency. The current best fit point for the sterile analysis is shown as a reference.

Table 1
Summary of the measured $\bar{\nu}_e - e$ scattering cross sections from reactor antineutrino experiments. The columns show the fuel averaged proportions, the electron recoil energy window, and the reported observables.

Experiment	^{235}U	^{239}Pu	^{238}U	^{241}Pu	T_{thres}	Observable
TEXONO [11]	0.55	0.32	0.07	0.06	3–8 MeV	$\sigma = (1.08 \pm 0.21 \pm 0.16) \cdot \sigma_{SM}$
MUNU [10]	0.54	0.33	0.07	0.06	0.7–2 MeV	(1.07 ± 0.34) events/day
Rovno [9]	$\simeq 1.0$	–	–	–	0.6–2 MeV	$\sigma = (1.26 \pm 0.62) \times 10^{-44}$ cm^2/fission
Krasnoyarsk [8]	$\simeq 1.0$	–	–	–	3.15–5.175 MeV	$\sigma = (4.5 \pm 2.4) \times 10^{-46}$ cm^2/fission

of CENNS, opening a promising new era of low energy neutrino experiments.

In this section we will study four different proposals that plan to use a reactor as their antineutrino source. They are the TEXONO, MINER, RED100, and CONNIE experiments, that we describe briefly in what follows.

- The TEXONO Collaboration has proposed the use of high purity Germanium-based detectors, with a threshold energy of $T_{thres} \sim 100$ eV [63,67]. The Collaboration expects to develop a modular detector and reach 1 kg mass for the target. The reactor flux would come from the Kuo-Sheng nuclear power plant and the detector would be located 28 m away from the reactor. For a quenching factor $Q_f = 0.25$ the expected number of events would be 4000 kg^{-1} year^{-1} [63].
- The MINER Collaboration will use a detector made of ^{72}Ge and ^{28}Si with a $2:1$ proportion and with a threshold energy, $T_{thres} \sim 10$ eV. A TRIGA-type pool reactor will deliver an antineutrino flux with a fuel average proportion of (^{235}U:^{238}U:^{239}Pu:^{241}Pu) given by [65] (0.967:0.013:0.02:0.001). With this special type of reactor, the detector can be located at a distance of 1–3 m from the source. An event rate of 5–20 kg^{-1} day^{-1} is forecast for this configuration [68]. In our simulations we will consider a 20 kg ^{72}Ge detector with one year of data taking at an event rate of 5 events kg^{-1} day^{-1}.
- The Kalinin power plant has also a program to detect CENNS. At least two different options appear in the literature. One is a germanium detector, νGeN [69], while the other one considers the use of liquid Xenon, RED100 [70]. We focus in the Xenon case as this material has been of interest for different experimental groups [71] and it is a different target with an energy threshold of $T_{thres} \sim 0.5$ keV [72]. The expected distance to the Kalinin reactor is about 19 m and they expect to detect 1020 events per day [73]. The expected fiducial mass is 100 kg [70]. As in the previous proposals, we consider one year of data taking.
- The CONNIE Collaboration [64] is currently working at the Angra-2 reactor using Charged-Coupled Devices (CCD's) as a detector, at 30 m from the reactor. It is expected that CCD technology can reach an energy threshold of 28 eV [74] and 16.1 events per day for one kg of material. We will consider again one year of data taking.

In order to calculate the number of events for any of the above proposals, we use the following expression for the cross section,

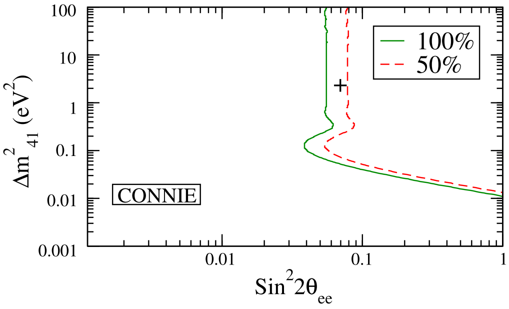

Fig. 4. Exclusion regions for the CONNIE proposal. The solid (green) line correspond to a detector with 100% efficiency and the dashed (red) lines a 50% efficiency. The current best fit point for the sterile analysis is shown as a reference.

$$\left(\frac{d\sigma}{dT}\right)^{\rm coh}_{\rm SM} = \frac{G_F^2 M}{2\pi}\left[1-\frac{MT}{E_\nu^2}+\left(1-\frac{T}{E_\nu}\right)^2\right] \times\left\{[(Zg_V^p+Ng_V^n)F(q^2))]^2\right\} \tag{5}$$

here, M is the mass of the nucleus, E_ν is the neutrino energy, T is the nucleus recoil energy, $F(q^2)$ is the nuclear form factor, and the neutral current vector couplings (including radiative corrections) are given by [27]

$$g_V^p = \rho_{\nu N}^{NC}\left(\frac{1}{2}-2\hat{\kappa}_{\nu N}\hat{s}_Z^2\right)+2\lambda^{uL}+2\lambda^{uR}+\lambda^{dL}+\lambda^{dR}$$
$$g_V^n = -\frac{1}{2}\rho_{\nu N}^{NC}+\lambda^{uL}+\lambda^{uR}+2\lambda^{dL}+2\lambda^{dR} \tag{6}$$

where $\rho_{\nu N}^{NC} = 1.0082$, $\hat{s}_Z^2 = \sin^2\theta_W = 0.23126$, $\hat{\kappa}_{\nu N} = 0.9972$, $\lambda^{uL} = -0.0031$, $\lambda^{dL} = -0.0025$, and $\lambda^{dR} = 2\lambda^{uR} = 7.5\times 10^{-5}$ [75]. We have checked that, for a first analysis of the expected sensitivity to a sterile neutrino signal, the corresponding form factors, $F(q^2)$, will not play a significant role[2] and, therefore we have taken them as unity in what follows. For estimating the number of expected events (SM) in the detector, we use the expression,

$$N^{\rm SM}_{\rm events} = t\phi_0\frac{M_{\rm detector}}{M}\int_{E_{\nu\rm min}}^{E_{\nu\rm max}}\lambda(E_\nu)dE_\nu\int_{T_{\rm min}}^{T_{\rm max}(E_\nu)}\left(\frac{d\sigma}{dT}\right)^{\rm coh}_{\rm SM}dT, \tag{7}$$

where $M_{\rm detector}$ is the mass of the detector, ϕ_0 is the total neutrino flux, t is the data taking time period, $\lambda(E_\nu)$ is the neutrino spectrum, E_ν is the neutrino energy, and T is the nucleus recoil energy. The maximum recoil energy is related with the neutrino energy and the nucleus mass through the relation $T_{\rm max}(E_\nu) = 2E_\nu^2/(M+2E_\nu)$. In all the cases we will consider one year of data taking.

For the oscillation to a fourth sterile family, we will consider the two families case in vacuum, where the number of events is

$$N^{\rm NS}_{\rm events} = t\phi_0\frac{M_{\rm detector}}{M}\int_{E_{\nu\rm min}}^{E_{\nu\rm max}}\lambda(E_\nu)P^{\rm SBL}_{\nu_\alpha\to\nu_\alpha}dE_\nu \times\int_{T_{\rm min}}^{T_{\rm max}(E_\nu)}\left(\frac{d\sigma}{dT}\right)^{\rm coh}_{\rm SM}dT. \tag{8}$$

In the above equation, $P^{\rm SBL}_{\nu_\alpha\to\nu_\alpha}$ represents the neutrino survival probability as expressed in Eq. (1). The differential cross section has just been discussed above, and the antineutrino flux will depend on the specific reactor under consideration. With this expression we can make a forecast for different experimental setups. We will consider the case of the MINER, RED100, and TEXONO proposal with the fluxes and thresholds mentioned above. We will assume that each experiment will measure exactly the standard prediction for the three active neutrino picture. With this hypothesis we will obtain an expected χ^2 analysis assuming only statistical errors.

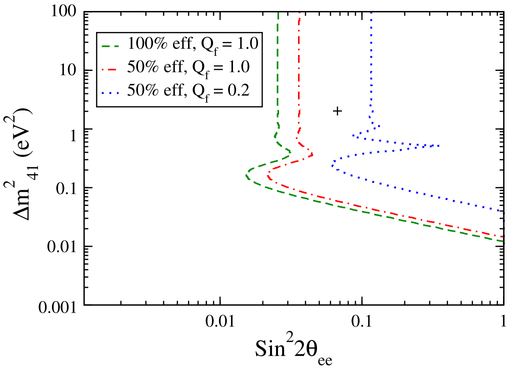

Fig. 5. Expected sensitivity for a reactor antineutrino experiment with a detector based on CENNS. We consider the TEXONO proposal as a reference with a Germanium detector. The three different exclusion regions correspond to a 90% CL for different combinations of efficiency and energy threshold: The most restrictive region is for a 100% efficiency and a 100 eV threshold ($Q_f = 1$), while the less restrictive case is for a 50% efficiency and a relatively high energy threshold of 500 eV ($Q_f = 0.2$). Finally the intermediate case shown in the figure is for a 50% efficiency and a 100 eV threshold ($Q_f = 1$).

The result of these computations for the MINER Collaboration is shown in the Fig. 2, where we have considered two different baselines of 1 m and 3 m. Since we are using only statistical errors, our analysis can be considered as very optimistic. In order to consider the more realistic counterpart, we have also shown in the same figure the case where the detector can only achieve a 50% efficiency. We can notice that for a baseline of 1 m the MINER Collaboration could exclude the current best fit point to the sterile neutrino analysis [60]. A similar analysis was done for the case of the RED100 proposal where we have considered the Kalinin nuclear power plant as the antineutrino flux source. We show in Fig. 3 the case of two different baselines and two possible efficiencies. The expectative to improve the current constraints on the mixing with a sterile neutrino is even more promising in this case, despite the relatively high detection energy threshold. In the case of the CONNIE proposal, we have performed a similar analysis, shown in Fig. 4 where it is also possible to reach the region of interest for the sterile signal.

We have also analyzed the case of the TEXONO proposal. The results are shown in Fig. 5. As in the previous cases, we have also considered different possibilities for this proposal. In particular, we take into account different quenching factors for the detector. This factor represents the ratio of the electron recoil to nucleus recoil energy [77], which gives us an important correction since the detector response to a nucleus recoil energy is different from the response coming from electron calibration sources. The quenching factor is given by

$$Q_f = \frac{E_{ee}}{E_{Nr}}, \tag{9}$$

where E_{ee} represents the electron equivalent energy and E_{Nr} is the nuclear recoil energy. In the case of the TEXONO experiment, we calculated the expected number of events for the quenching factors $Q_f = 1$ and $Q_f = 0.2$.

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[2] We have computed the form factor with the effective model of Ref. [76].

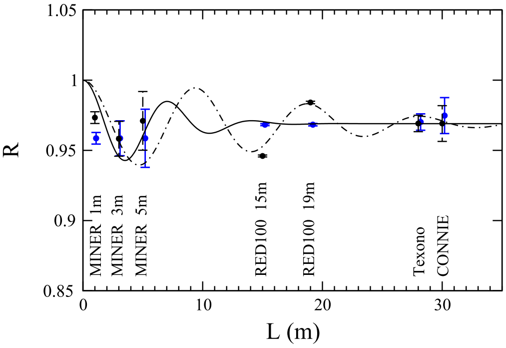

Fig. 6. Ratios *R* of predicted to expected rates for different proposed CENNS experiments. We have taken the Mueller spectrum as a reference in our calculations. Different baselines are shown for some detectors, taking into account that the proposals are still under discussion. The black dots show the expected ratio for the case of a sterile neutrino with a $\sin^2 2\theta_{ee} = 0.062$ and $\Delta m^2 = 1.7$ eV. The blue dots give the ratio for the case of a decrease in the ^{235}U of 5% as proposed in a recent article [42]. The black line represents the average probability for a mean energy of 4 MeV, and the dotted black curve corresponds to an energy of 6.5 MeV, both with an energy resolution of 15%. And finally the error bars account for the statistical errors. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The regions of mixing angle and squared-mass splitting favored by different combinations of quenching factors and detector efficiencies are shown in the Fig. 5. The results are in agreement with the previous work of Ref. [34] and shows other cases with a different quenching factor. The expectations for this proposal are competitive with the MINER and RED100 proposals as can be seen from Figs. 2 and 3.

We conclude this section comparing the expected signal for these proposals in two very different situations. Recently, the theoretical estimates for the antineutrino flux have been under deep scrutiny (see for instance [42,78,79]) and the reactor anomaly might be solved by a re-evaluation of the neutrino fluxes [42,79]. In this case, it is also possible that the CENNS experiments give a confirmation of this result, especially if several CENNS experiments with different baselines are performed, as seems to be the case. This situation is illustrated in Fig. 6, where we show what will be the antineutrino rate measured by these proposals if a 5% decrease in the ^{235}U is considered [42] (without any sterile effect). On the other hand, we also show the expected ratio for the same experiments, in the case that the sterile neutrino is the responsible for the deficit. For this case we consider $\Delta m^2 = 1.7$ eV^2 and $\sin^2 2\theta_{ee} = 0.062$, according to the most recent fit of antineutrino disappearance data [60]. As expected, the different baselines will give a different ratio for the sterile solution. The situation is different if the reactor anomaly is due to a correction in the antineutrino flux, where the expected number of events will be different than for the oscillation explanation, especially for the RED100 and the MINER (1 m) cases. In this case, as expected, the complementarity of different experiments using different baselines, thresholds, and fuel proportions could be very helpful in discriminating what is the real explanation of the reactor anomaly.

4. Conclusions

In this work we have studied the reactor anomaly in the context of future CENNS experiments and in antineutrino electron scattering data from short baseline reactor neutrino experiments. Concerning antineutrino–electron scattering we conclude that this interaction can give limited information due to the relatively poor statistics. On other hand, the recent observation of CENNS by the COHERENT Collaboration strongly motivates the further exploration of physics beyond the Standard Model in this context. We show that CENNS experiments could play an important role in the determination, or exclusion, of the sterile signal. Particularly, the RED100, TEXONO, MINER, and CONNIE proposals could test the current best fit point of the sterile allowed parameter space. Regarding the need of a precise antineutrino flux determination, CENNS is particularly attractive, since the detection technique is different from that of IBD detectors. In this case, we obtained the ratios between predicted and expected data in two different cases: considering sterile neutrinos and taking a decrease in the antineutrino flux as it is suggested by some recent works. Both situations could be of interest in order to explain the reactor antineutrino anomaly.

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