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The reactor antineutrino anomaly and low energy threshold neutrino experiments

B.C. Cañas [a,b], E.A. Garcés [a], O.G. Miranda [a,*], A. Parada [b]

[a] Departamento de Física, Centro de Investigación y de Estudios Avanzados del IPN, Apdo. Postal 14-740, 07000 Ciudad de México, Mexico
[b] Universidad Santiago de Cali, Campus Pampalinda, Calle 5 No. 6200, 760001, Santiago de Cali, Colombia

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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

* Corresponding author.
E-mail addresses: blanca.canas00@usc.edu.co (B.C. Cañas), egarces@fis.cinvestav.mx (E.A. Garcés), omr@fis.cinvestav.mx (O.G. Miranda), alexander.parada00@usc.edu.co (A. Parada).

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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]

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

where

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

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

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

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, $P^{\rm SBL}_{\nu_\alpha\to\nu_\alpha}$ 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]

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

where m_e stands for the electron mass and G_F is the Fermi constant. In this expression, $g_L = 1/2+\sin^2\theta_{\rm W}$ and $g_R = \sin^2\theta_{\rm W}$ 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 $\sigma(T) = 0.08\ {\rm T}^{0.7}$ [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.

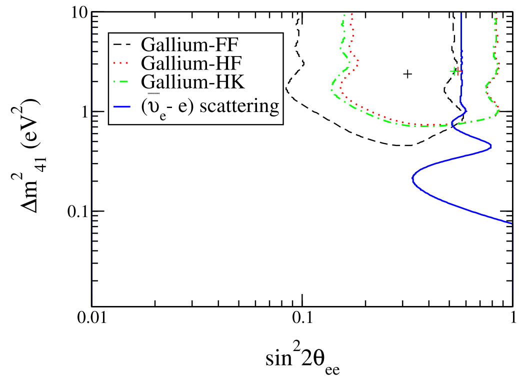

Fig. 1. Restrictions for a sterile neutrino from a combined analysis of neutrino electron scattering from reactor experiments at 90% C L (blue solid line). We also show for comparison, the results for the Gallium anomaly [55] in the three cases discussed in the text. The best-fit values are indicated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

[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].