Search for exotic neutrino interactions using solar neutrinos in the CDEX-10 experiment

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— Various cosmological and astrophysical observations at different scales reveal phenomena beyond the Standard Model (SM) that require new physics to explain. Neutrino is one of the most important directions. The measurement of non-standard interaction (NSI) in the neutrino sector provides an attractive approach to probe the new physics beyond the SM. Current experimental efforts on neutrino measurements are being conducted with different neutrino sources, such as reactor neutrinos, accelerator neutrinos, and radioactive sources. Besides these terrestrial sources, neutrinos can also be produced from astrophysical sources, such as stellar, Supernova, atmosphere, and others. In this letter, the exotic interactions between either active or sterile neutrino that comes from the Sun and the electron/nucleus are investigated. The results are interpreted under two physics scenarios. In the first case, $U(1)_{B-L}$ is considered where the corresponding gauge boson induces the interaction between the active neutrino and the electron/nucleus. In the second case, a dark photon from $U(1)'$ is considered as the mediator between sterile neutrino and electron/nucleus.
The detector array consists of three triple-element germanium detector strings encapsulated in the copper vacuum tubes and immersed in Liquid Nitrogen (LN$_2$) for cooling and shielding. The 20-cm-thick high-purity oxygen-free copper in the LN$_2$ cryostat operates in a polyethylene room with 1-m-thick walls at CJPL-I. The configuration of the detector system was previously described in detail[35,36]. CDEX-10 has been under stable data taking conditions since February 2017, and the analysis threshold achieves 160 eVee (electron equivalent energy). Several physical results about DM are derived, such as constraints on DM-nucleus scattering down to $m_\chi \sim 2$ GeV/$c^2$ using a 102.8 kg day exposure[35], constraints on the solar dark photon effective mixing parameter[37], constraints on sub-GeV DM boosted by cosmic rays[39], and constraints on sub-GeV DM-electron scattering[40], are derived from the total 205.4 kg day exposure.

Within the SM, neutrinos can interact with germanium and produce detectable electronic and nuclear recoils through coherent elastic neutrino-nucleus scattering (CE$
u$NS) and electroweak interactions. A popular setup for exotic neutrino interactions is the possibility that a gauge boson mediates the neutrino interaction with electron and/or quarks. Here, in general, we assume

$$\mathcal{L}_{\text{int}} \supset g_n e_\nu \gamma^\mu A_\mu + g_g q_\nu \gamma^\mu A_\mu + g_g q_\nu q' P_{L,R} \nu A_\mu$$

(1)

where $A'$ is the extra mediator with mass $M_{A'}$ from an $U(1)$ gauge group, and $\nu$ can be either active or sterile neutrino. $g_{e,q,v}$ are the couplings between $A'$ with the corresponding fermions. The neutrino-induced scattering rate is

$$\frac{dR}{dE_r} = N_T \times \int_{E_{\nu,\text{min}}}^{\infty} \frac{d\Phi}{dE_\nu} \frac{d\sigma}{dE_r} dE_\nu,$$

(2)

where $N_T$ is the number of target nuclei or electrons per unit of mass of the detector material (for nuclear and electronic recoils, respectively), $E_{\nu,\text{min}}$ is the minimum neutrino energy required to generate recoil energy $E_r$, $\frac{d\Phi}{dE_\nu}$ is the differential flux of neutrinos, and $\frac{d\sigma}{dE_r}$ is the differential cross section, which depends on the nature of the interaction. For the case in Eq. [1], the enhancement of the neutrino-electron scattering and neutrino-nucleus scattering cross section are given by

$$\frac{d\sigma(\nu e \rightarrow \nu e)}{dE_r} = \frac{(g_n g_e)^2 m_e}{4\pi p_\nu^2 (M_{A'}^2 + 2E_r m_e)^2} \times [2E_r^2 + E_\nu^2 - 2E_r E_\nu - E_r m_e - m_\nu^2],$\n
(3)

$$\frac{d\sigma(\nu N \rightarrow \nu N)}{dE_r} = \frac{(g_n g_e)^2 m_N F^2(E_r)}{4\pi p_\nu^2 (M_{A'}^2 + 2E_r m_N)^2} \times [2E_r^2 + E_\nu^2 - 2E_r E_\nu - E_r m_N - m_\nu^2],$$

(4)

where $E_r$ is the recoil energy of the target, $E_\nu$ is the neutrino energy, $m_{e,N,\nu}$ are the mass of the electron, target nucleus, and neutrino. $M_{A'}$ is the mass of the extra gauge boson. $g_N$ is the coherent coupling of the gauge boson with the nucleus: $g_N = g_p Z + g_n (A - Z)$ with $g_p = 2g_n + g_d$ and $g_n = g_u + 2g_d$. $F^2(E_r)$ is the nuclear form factor, which describes the loss of coherence due to the internal structure of the nucleus. In this work, the conventional Helm form factor[43,44] is adopted. For the $\nu - e$ scattering case, the observed total deposit energy $E_{\text{det}}$ is equal to the real electron recoil energy $E_r$. For the $\nu - N$ scattering case, the observed total deposit energy $E_{\text{det}}$ is different from the real nuclear recoil energy $E_r$ and should be corrected by the quenching factor, $E_{\text{det}} = Q_{nr} E_r,$ where the quenching factor $Q_{nr}$ in Ge is calculated by the TRIM package[45] in this work. The differential event rates in germanium for the electronic/nuclear recoil from the CE$
u$NS in the SM for solar neutrino and several physical benchmarks (see discussion below) are calculated and shown in Fig. [1] where the energy resolution of CDEX-10 was considered, and its standard deviation is $35.8 + 16.6 \times (E/\text{keV})^{1/2}$ (eV)[35,36,39,40].

Within the framework, two physical scenarios are investigated: (1) Model-I: Active neutrinos from the Sun and SM particles coupled through $U(1)_{B-L}$ gauge boson; and (2) Model-II: Sterile neutrinos from the Sun and SM particles coupled through dark photon which kinetically mixes with photon. Additionally, the constraints based on 205.4 kg day exposure data from CDEX-10 are calculated. At the sub-keVee energy range relevant to this analysis, background events are dominated by Compton scattering of high-energy gamma rays and internal radioactivity from long-lived cosmogenic isotopes. In Fig. [1] the black points show the measured spectrum after subtracting the contributions from L- and M-shell x-ray peaks derived from the corresponding K-shell x-ray intensities. Following our previous DM analysis[35,37,40], a flat background contribution from the Compton scattering of high-energy gamma rays is assumed to apply a minimum-$\chi^2$ analysis to the residual spectrum at the range of $0.16 - 2.16$ keVee.

**Model-I: Active neutrinos and SM particles coupled through $U(1)_{B-L}$ gauge boson.**—The Hidden Sector and the existence of one new gauge boson have been discussed for ages and remain popular[46,47]. One of the mechanisms, a new gauge boson that interacts with the SM particles through a $U(1)_{B-L}$, is widely studied[27]. It significantly improves the region of interest (ROI, <2 keV) of DM direct detection experiments. The contribution of the enhancement can be classified into two categories: pure contribution and the interference between the extra gauge boson and the SM, while the latter contribution is almost negligible in the CDEX-10 experiment and the currently-running generation of experiments[35,48,49], which are insensitive to the SM interaction of solar neu-
FIG. 1. The measured (black points with error bars) event rate and expected (colored lines) event rates under the two scenarios of (1) Model-I: Active neutrinos from the Sun and SM particles coupled through $U(1)_{B-L}$ gauge boson; and (2) Model-II: Sterile neutrinos from the Sun and SM particles coupled through dark photon which kinetically mixes with photon, in the case of (a) $\nu-e$ scattering and (b) $\nu-N$ scattering. Lines (A) and (B) correspond to Model-I, while (C) and (D) correspond to Model-II. For the parameters of lines (C) and (D), the parameter $\sin 2\theta_{14}$ has been absorbed into the $g_{\nu e}$ and $g_{\nu N}$. The energy resolution of CDEX-10 was considered, and its standard deviation is $35.8 \pm 16.6 \times (E/\text{keV})^{1/2} \ (\text{eV})$ [35, 36, 39, 40]. For the $\nu-N$ scattering case, the quenching factor in Ge is calculated by the TRIM package [45]. The measured spectrum of CDEX-10 is shown in black points with error bars, which shows the residual spectrum with the L- and M-shell X-ray contributions subtracted in the region of 0.16–2.16 keVee, with a bin width of 100 eVee [35, 39, 40].

FIG. 2. Constraints on a $U(1)_{B-L}$ gauge boson with coupling $g_{B-L}$ and mass $M_{A'}$. The 90% C.L. bounds from CDEX-10 solar neutrino analysis are shown in red, where the solid line represents $\nu-e$, and the dashed line represents $\nu-N$. The other bounds superimposed are described in Refs. [27, 28, 52–69]. The combined curve of $\nu-e$ constraints [27] from GEMMA, Borexino, TEXONO-CsI, and CHARM II ($\tau_\nu$) is shown; the color of the curve varies in different mass regions, indicating where the stringiest constraints come from each region.

The expected event rates for $\nu-e$ and $\nu-N$ scattering with specific parameters (Case (A) and (B)) are shown in Fig. 1. The B16-GS98 solar model (also referred to as the high-metallicity, or HZ model) is considered in this work. Values for the neutrino fluxes are taken from Ref. [50]. With predicted scattering event rates of $\nu-e$ and $\nu-N$ from solar neutrinos, compared with the measured rate, the upper limits at 90% confidence level (C.L.) on corresponding parameters are derived, using the unified approach [51]. In Fig. 2 the 90% C.L. bounds from CDEX-10 solar neutrino analysis are shown in red, where the solid line represents $\nu-e$, and the dashed line represents $\nu-N$. Comparing the constraints derived from $\nu-e$ scattering and $\nu-N$ individually, we see that each channel allows us to better probe a different region of the parameter space. For masses $M_{A'} < 2 \text{ MeV}$, the inclusion of $\nu-e$ scattering in our analysis allows us to probe smaller couplings, while above this mass the more stringent constraints come from $\nu-N$ scattering, which is mainly due to the factor $(M_{A'}^2 + 2E_{\nu}m_{e}/N)^2$ in Eqs. 3 and 9 and the target mass of $\nu-e$ is smaller than that of $\nu-N$. Hence the expected event rate of $\nu-e$ is larger when the mass of the gauge boson is relatively small, but fades as the mass of the gauge boson increases.

For $\nu-e$ scattering, the upper limits for the coupling constant of the $U(1)_{B-L}$ gauge group are obtained as $g_{B-L} < 1.45 \times 10^{-6}$ for $M_{A'} = 1 \text{ keV}$, and $g_{B-L} < 8.74 \times 10^{-4}$ for $M_{A'} = 10 \text{ MeV}$. CDEX-10 is more sensitive in the low-mass region of gauge boson than Borexino [67].
whereas a higher background level than Borexino will lead to an overtake in the high-mass region. However, the constraints were not expected to be competitive with other experiments, such as GEMMA \[68\] with a larger neutrino flux from the reactor; this analysis would act as proof-of-concept for future analyses at CDEX-50.

Model-II: Sterile neutrinos and SM particles coupled through dark photon.— The dark photon in Hidden Sector is one of the possible candidates for DM, and it can also act as the mediator between SM particles and sterile neutrinos within the Hidden Sector \[28\], increasing the scattering rate of sterile neutrinos and detector targets. The sterile neutrinos in this scenario are singlets under the SM gauge group but charged under a new $U(1)'$ gauge group. However, SM particles could only be coupled to the $A'$ gauge boson (which we call the “dark photon”) through a small kinetic mixing $\varepsilon$ with the photon. In this case, in accordance with Eq. \[1\], we have $g_e = g'$ and $g_f = \varepsilon Q$ for $f = e, q$, where $\varepsilon$ is the kinetic mixing parameter, $Q$ is the charge of the corresponding fermion, and $g'$ is the $U(1)'$ gauge coupling constant.

Under this scenario, the interaction between target and sterile neutrinos is enhanced compared with that for active neutrinos. The expected event rates are also related to the flux of sterile neutrinos. In this work, the light sterile neutrinos with a mass less than $\mathcal{O}(100)$ keV are considered and a small admixture of sterile neutrinos to the solar neutrino flux can be produced by oscillation before the neutrinos reach the Earth \[28\]. The vacuum oscillation probability in a two-flavor approximation is given by the usual expression \[28\]

$$P(\nu_a \to \nu_s) = \sin^2 2\theta_{14} \sin^2(\frac{\Delta m^2_{41} L}{4E}), \quad \text{(5)}$$

where $\theta_{14}$ is the effective active-sterile neutrino mixing angle in vacuum, $\Delta m^2_{41} = m_4^2 - m_1^2$ is the splitting between the squared mass of the most sterile mass eigenstate ($m_4$) and the most active mass eigenstate ($m_1$) in vacuum, $L$ is the distance neutrino traveled, and $E$ is the neutrino energy.

The expected event rate under this scenario is similar to Model-I as shown in Fig. \[1\] (Case (C) and (D)), and it leads to a larger enhancement of the energy spectrum, under the same parameters, with an increase proportionate to $E_r^{-2}$ in the relevant region. Note that in producing the event rate in Fig. \[1\] the extra dependence on $\sin 2\theta_{14}$ is absorbed into $g_{e,N}g_{\nu}$. It is hard for reactor neutrino experiments to place a constraint on this model because of the negligible flux of sterile neutrino oscillated from reactor active neutrino due to the short distance between the reactor and detector in Eq. \[5\] whereas the solar neutrino experiments using solar neutrino as the source remains unaffected \[28\]. The constraints on the kinetic mixing parameter depend on $\Delta m^2_{41}$ and $g^2\sin^2 2\theta_{14}$.

Following similar $\chi^2$ minimization analysis discussed above, no significant signal of $\nu - e$ or $\nu - N$ scattering is observed. The 90% C.L. bounds from CDEX-10 solar neutrino analysis are shown in red, where the solid line represents $\nu - e$, and the dashed line represents $\nu - N$. The grey lines (CDEX-10) represent previous CDEX-10 constraints on kinetic mixing parameter of dark photon using the same dataset with different theoretical framework \[37\]: the dashed line stands for solar dark photon and the solid line stands for dark photon DM. The other bounds superimposed are described in Refs. \[27, 28, 57, 67, 70, 71\], and the limit from TEXONO \[74\] is 95% C.L.

FIG. 3. Constraints on light $A'$ gauge bosons kinetically mixed with the photon as a function of the $M_{A'}$ mass and the kinetic mixing parameter $\varepsilon$, at the parameter choice of $\Delta m^2_{41} = (10 \text{ keV})^2$ and $g^2\sin^2 2\theta_{14} = 10^{-4}$, following earlier phenomenological interpretations of Borexino data by Roni et al. \[28, 67\]. The 90% C.L. bounds from CDEX-10 solar neutrino analysis are shown in red, where the solid line represents $\nu - e$, and the dashed line represents $\nu - N$. The grey lines (CDEX-10) represent previous CDEX-10 constraints on kinetic mixing parameter of dark photon using the same dataset with different theoretical framework \[37\]: the dashed line stands for solar dark photon and the solid line stands for dark photon DM. The other bounds superimposed are described in Refs. \[27, 28, 57, 67, 70, 71\], and the limit from TEXONO \[74\] is 95% C.L.
limit for the kinetic mixing parameter $\varepsilon$ in the mass range below 50 keV in the model where sterile neutrinos and SM particles coupled through dark photon.

Summary.—In this letter, the neutrino (either active or sterile) interaction with the electron and nucleus is analyzed. The observed event rate is translated into upper limits on the couplings under two beyond SM scenarios for exotic neutrino interactions using solar neutrino, one with $U(1)_{B-L}$ gauge boson induced interaction between active neutrinos and electron/nucleus and another with a kinetically mixed dark photon induced interaction between sterile neutrino and electron/nucleus, which can enhance both the $\nu - e$ and $\nu - N$ interactions in the ROI of DM direct detection experiments. The constraints on the two models are derived using the 205.4 kg day dataset from the CDEX-10 experiment. For Model-II with sterile neutrino, we examined a new parameter space for dark photon masses below 1 eV$/c^2$ at some typical choices of $\Delta m^2_{31}$ and $g^2\sin^22\theta_{14}$, which was previously unexplored by DM direct detection experiments and neutrino experiments. This extends the reach in the corresponding scenario of the laboratory measurements.

CDEX-50, the third phase of the CDEX experiment, is under construction. A 50-kg germanium detector array will be run in a low radioactive environment, and the radioactive background will be further reduced to $\sim 0.01$ cpkdd in the sub-keV region [40], which is much lower than that of CDEX-10. Thus, it is expected that the constraints on the mass and couplings of an extra gauge boson can be further improved.

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