A new scheme for short baseline electron antineutrino disappearance study

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Abstract. A new scheme for the short baseline electron antineutrino ($\bar{\nu}_e$) disappearance study is investigated. We propose to use an intense neutron emitter, $^{252}$Cf, which produces $^8$Li isotope through the $^7$Li$(n,\gamma)^8$Li reaction; $^8$Li is a $\bar{\nu}_e$ emitter via $\beta^-$ decay. Because this $\bar{\nu}_e$ source needs neither accelerator nor reactor facilities, the $\bar{\nu}_e$ can be placed on any neutrino detectors as closely as possible. This short baseline circumstance with a suitable detector enables us to study the existence of possible sterile neutrinos, in particular, on 1 eV mass scale. Also, complementary comparison studies among different neutrino detectors can become feasible by using $\bar{\nu}_e$ from the $^8$Li source. As an example, applications to hemisphere and cylinder shape scintillator detectors are performed in detail with the expectation signal modification by the sterile neutrino. Sensitivities to mass and mixing angles of sterile neutrinos are also presented for comparison with those of other neutrino experiments.

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One of open issues in the particle and neutrino physics is the existence of hypothetical fourth neutrino which may be mixed with active neutrinos [1]. This fourth neutrino, so-called sterile neutrinos (νs), is claimed to play important roles of explaining some anomalies reported in LSND [2], MiniBoone [3], reactor experiments [4], and gallium experiments [5]. A few experiments with compact neutrino detectors and reactor facilities [6, 7, 8, 9, 10, 11] or antineutrino sources from radioactive isotopes [12, 13, 14] or an accelerator-based IsoDAR (isotope decay-at-rest) [15, 16, 17] are proposed to search the existence of νs.

By using compact neutrino detectors such as DANSS [6], NEUTRINO4 [7], NUCIFER [8], PANDA [9], PROSPECT [10], and STEREO [11], experiments have been planned to measure reactor neutrinos at a distance of several meters. KamLAND (CeLAND) [13] and Borexino (SOX) [14] plan to perform experiments by using antineutrino generators of unstable isotopes 144Ce-144Pr of a radioactivity of 100 kCi, where neutrino energies are lower than 3 MeV. As another type of antineutrino source, 8Li was suggested by using an accelerator-based IsoDAR concept [16, 17]. Electron antineutrinos (νe) were assumed to be emitted from 8Li through β− decay with energies of up to ∼13 MeV. Because these energies are higher than those from 144Ce-144Pr, 8Li can be used for study of νs spectrum distortion in the energy region of 5 MeV < Eν < 7 MeV, where some distortions or anomalies were reported by reactor antineutrino experiments (Daya Bay [18], Double Chooz [19] and RENO [20, 21]).

In this letter, as a new 8Li generator, we propose a fissionable isotope of 252Cf radioactive isotope-based νe production scheme. In particular, our 8Li generator can be placed on any neutrino detectors such as Borexino [22], JUNO [23], KamLAND [24], LENA [25] and SNO+ [26], etc., because one does not need any accelerator or reactor systems. As an intense neutron emitter, 252Cf is used for productions of 8Li. 252Cf with a half-life of 2.64 yr emits neutrons with an average energy of 2 MeV via spontaneous fissions. The neutron emission rate of 1 gram of 252Cf is 2.34 × 10^{12} neutrons per second (n/s). For energy distribution of neutrons from 252Cf we take Watt fission spectrum [27, 28, 29] in this work.

We consider three different types of geometrical setups for productions of 8Li as shown in Fig. 1 Figure 1 (a, d) (setup I) shows a simple setup case with 99.99% enhanced 7Li convertor and 252Cf surrounded by the Li convertor.‡ The Li convertor has a cylindrical shape of a radius of 100 cm and a length of 200 cm based in Ref. [16]. In Fig. 1(b, e) (setup II), we add carbon (graphite) material as a neutron reflector to the setup I. The carbon is preferred as the neutron reflector due to its low absorption cross section and high elastic scattering cross section. This concept is known as the Adiabatic Resonance Crossing (ARC) [30] for the transmutation of long-lived radio isotopes in the nuclear waste and the medical radioisotope production [31, 32, 33]. With the carbon reflector, we can increase production yield of 8Li even though the amount of 7Li is less than that of the setup I. The setup III in Fig. 1(c, f) has two carbon reflectors. One is

‡ A 252Cf source is enclosed with the stainless steel case, but the presence of the case does not affect present work.
surrounded by the Li convertor and another wraps the Li convertor.

The production rate of $^8$Li by neutrons from $^{252}$Cf is estimated by using GEANT4 code (v. 10.1) [34, 35]. High precision models with G4Neutron Data Library (G4NDL) 4.5 are used in the present work. The data in G4NDL 4.5 come largely from the Evaluated Nuclear Data File (ENDF/B-VII) library [36]. Simulation snap shots for the $^8$Li generator setup I, II, and III are shown in Fig. 1 (g, h, i), respectively.

First, we calculate the production yield of $^8$Li for the case of setup I depicted in Fig. 1 (g), and obtain the yield of 0.0045 $^8$Li per neutron ($^8$Li/n). The production yields of $^8$Li for the setup II and III are sensitive to the thickness of carbon reflector, $T_1$ and $T_2$, in Fig. 1. As the thickness of the reflector increases, numbers of the collisions between the neutron and the carbon also increase. Thus, probabilities for the neutron capture by $^7$Li can also increases. If the $T_1$ is too thick, however, it becomes hard for the scattered neutron to escape from the inner carbon, namely, these neutrons are rarely absorbed to $^7$Li.

Figure 2 (a) shows the dependence of the $^8$Li yields on the thickness of carbon reflector ($T_1$) for setup-II. Yields of $^8$Li increase when $T_1$ increases up to 43 cm. Maximum yield of $^8$Li is 0.157 $^8$Li/n at $T_1 = 43$ cm, where the yield is larger than

\[ \text{For simplicity, simulations have been performed with 500 neutrons generation from } ^{252}\text{Cf where the neutron has a Watt fission spectrum in Refs. [27, 28, 29].} \]
Figure 2. (Color online) (a) $^8$Li isotope yields for setup II with respect to $T_1$. (b) $^8$Li isotope yields for setup III with respect to $T_2$, where $T_1$ is set to be 43 cm which is an optimal thickness in (a).

those for setup-I about 35 times. As the $T_1$ increases more than 43 cm, yields of $^8$Li decrease. In Fig. 1(h), un-captured neutrons by $^7$Li still can escape from the geometry. To further increase the yields of $^8$Li, additional carbon reflector with the thickness $T_2$ is considered to be located out of the Li convertor.

The production yield for $^8$Li with respect to $T_2$ is plotted in Fig. 2(b). Figure 2(a) shows that the optimal thickness of $T_1$ is 43 cm, and thus the same thickness is chosen for setup-III. As the $T_2$ increases, $^8$Li yields also increase up to 0.256 $^8$Li/n. With the $T_2$ larger than 50 cm, yields for $^8$Li are almost saturated. Maximum yields of $^8$Li for setup-III are larger than those for setup-II and setup-I by factors $\sim 1.6$ and $\sim 56.9$, respectively.

We obtained a result that the yields of $^8$Li increase to the maximum value at $T_1 = 43$ and $T_2 = 100$ cm of the setup III, where the production yield is 0.256 $^8$Li/n. $^8$Li with a half-life of 0.838 s emits $\bar{\nu}_e$ through $\beta^-$ decay. The electron anti-neutrinos from $^8$Li have continuous energy distribution, which is evaluated by using “G4RadioactiveDecay” \cite{37, 38} class based on the Evaluated Nuclear Structure Data File (ENSDF) \cite{39}.

Electron antineutrinos can be measured with two different neutrino reactions. One is $\bar{\nu}_e$ elastic scattering on electrons (ES), and another is inverse beta decay (IBD) reaction, $\bar{\nu}_e + p \rightarrow e^+ + n$. In ES, $\bar{\nu}_e$ can be indirectly measured by the scattered $e^-$ by liquid-scintillator (LS). Expected event rate for ES can be obtained from Refs. \cite{40, 41}. The event rate $(R_{\bar{\nu}_e}^{IBD})$ for IBD is written as

$$R_{\bar{\nu}_e}^{IBD} = n_p \int_{E_{th}}^{E_{max}} dE_p \Phi_{\bar{\nu}_e}(E_p) P_{\nu\bar{\nu}}(E_p) \sigma_{\nu\bar{\nu}}^{IBD}(E_{\bar{\nu}_e}) \ , \quad (1)$$

where $n_p$ is the number of target protons within a fiducial volume of the detector, $\Phi_{\bar{\nu}_e}(E_p)$ is the $\bar{\nu}_e$ flux from $^8$Li, $P_{\nu\bar{\nu}}(E_p)$ is the energy dependent $\bar{\nu}_e$ survival probability. The energy dependent cross section of IBD is approximately taken by \cite{42}

$$\sigma_{\nu\bar{\nu}}^{IBD}(E_{\bar{\nu}_e}) \approx p_e E_e E_{\bar{\nu}_e}^{-0.07056+0.02018\ln E_{\bar{\nu}_e}-0.001953} \ln^3 E_{\bar{\nu}_e} \times 10^{-43}[\text{cm}^2], \quad (2)$$

where $p_e$, $E_e$, and $E_{\bar{\nu}_e}$ are the positron momentum, total energy of the positron, and
In Fig. 3, energy distribution of $\bar{\nu}_e$ from $^8$Li and expected event rates of ES and IBD are presented, where $^8$Li is assumed to be produced by the setup III. For the calculation of neutrino oscillation, we use the $P_{\nu e}(E_\nu) (\equiv P_3)$ given by\footnote{This cross section agrees within few per-mille with the full calculation including the radiative corrections and the final-state interactions in IBD.}

$$P_3 = 1 - \sin^2 2\theta_{13} S_{23} - c_{13}^2 \sin^2 2\theta_{12} S_{12},$$ \hspace{1cm} (3)

where $S_{23} = \sin^2(\Delta m^2_{32} L/4E)$ and $S_{12} = \sin^2(\Delta m^2_{21} L/4E)$. Neutrino oscillation parameters are taken from a global fit from Ref.\cite{44}. For comparison, we chose the number of electrons ($n_e$) in LS for ES as the same as the numbers of protons ($n_p$) in LS for IBD. The reaction rates of ES turn out to be much smaller than those of IBD. Therefore, herefrom we only consider IBD for the following neutrino disappearance study.

The IBD reaction offers two signals in neutrino detections; one is a prompt signal due to annihilation of a positron, and another is a delayed signal of 2.2 MeV $\gamma$ ray via a neutron capture, which provides almost unambiguous antineutrino event detection. The two distinct detections give an efficient rejection of other possible backgrounds.

Note that various unstable isotopes which emit antineutrinos can be produced. In the Li convertor, $^3$H, $^6$He, and $^{10}$Be are produced as well as $^8$Li. However, $^3$H decays with a half-life of 12.3 y, and the production yields of $^6$He and $^{10}$Be are much lower than that of $^8$Li by factors of $10^4$ and $10^7$, respectively. $^{10}$Be, $^{12}$B, and $^{14}$C are produced in the carbon reflectors. Due to low yields of $^{10}$Be and $^{12}$B and a long half-life of $^{14}$C ($5.7 \times 10^3$ y), their contributions are marginal for the IBD neutrino detections.

There are background neutrinos such as neutrinos from fission product of $^{252}$Cf ($\nu_f$)
and geo-neutrinos ($\nu_{\text{geo.}}$). To see the effect of the $\nu_f$, we estimate flux and event rate for $\nu_f$ by using ENDF/B-VII and ENSDF data, and the results are compared with those from $^8\text{Li}$ ($\nu_{8\text{Li}}$) in Fig. 4. Figure 4 (a) shows that the $\nu_f$ are dominant in low energy regions. However, for $E_{\bar{\nu}_e} > 7$ MeV (corresponding to $E_{\text{vis}} > 6.22$ MeV), contributions of the $\nu_f$ are negligible compared to the $\nu_{8\text{Li}}$. Total expected event rate of $\nu_f$ for $E_{\bar{\nu}_e} > 7$ MeV in Fig. 4 (b) is smaller than those from $^8\text{Li}$ by three orders of magnitudes. With the neutrino energy cut of 7 MeV, we can remove the effect of $\nu_f$ in our work. KamLAND [45] and Borexino [46, 47] have measured a rate for $\nu_{\text{geo.}}$ (≈ a few events/(100 ton · yr)) due to the decay of U or Th in the Earth. Contributions of the $\nu_{\text{geo.}}$ is negligible compare to those of $\bar{\nu}_e$ from $^8\text{Li}$.

Electron-antineutrino survival probabilities in Eq. (1) by the 3+1 and 3+2 scenarios can be written as [16]

$$P_{3+1} = 1 - 4|U_{e4}|^2(1 - |U_{e4}|^2)\sin^2(\Delta m_{41}^2 \frac{L}{4E}),$$

$$P_{3+2} = 1 - 4[(1 - |U_{e4}|^2 - |U_{e5}|^2)$$

$$\times (|U_{e4}|^2\sin^2(\Delta m_{41}^2 \frac{L}{4E}) + |U_{e5}|^2\sin^2(\Delta m_{51}^2 \frac{L}{4E}))$$

$$+ |U_{e4}|^2|U_{e5}|^2\sin^2(\Delta m_{54}^2 \frac{L}{4E})],$$

where relevant parameters are taken from the best-fit points for the 3+1 and 3+2 scenarios from the reactor antineutrino data at Table 1 in Ref. [48].

The visible energy ($E_{\text{vis}}$) of the prompt signal due to a positron ($e^+$) is strongly correlated with the energy of $\bar{\nu}_e$ ($E_{\bar{\nu}_e}$), $E_{\bar{\nu}_e} \simeq E_{\text{vis}} + 0.78$ MeV, by which $\bar{\nu}_e$ energy spectrum can be reconstructed using $E_{\text{vis}}$. The spectral shape of $E_{\text{vis}}$ would give a valuable chance to check the existence of the fourth neutrino. To see the effect of $\nu_s$ using the shape analysis like Double Chooz, Daya Bay, and RENO experiments, event rates are estimated for two different types of LS detectors based on the JUNO [23] and the LENA [25] with respect to $E_{\text{vis}}$ in the following.
Figure 5. (Color online) (a) OpenGL picture showing simulation geometry for hemisphere type detector with $^8$Li generator. (b) Expected event rates, $R_3$, $R_{3+1}$ and $R_{3+2}$ by $P_3$, $P_{3+1}$ and $P_{3+2}$ models, and their ratios with respect to $E_{\text{vis}}$. Here $6 \times 10^{11} \bar{\nu}_e/s$ from the setup III source with $T_1 = 43 \text{ cm}$ and $T_2 = 100 \text{ cm}$ by 1 g of $^{252}$Cf is applied for the calculation.

Figure 6. (Color online) Same as in Fig. 5 except that the detector has a cylinder shape.

First, a hemisphere shape scintillator detector based on the JUNO [23] is considered. The present proposed $^8$Li generator requires the space of $T_1 = 43 \text{ cm}$ and $T_2 = 100 \text{ cm}$ in a detector. Thus, we consider a hemisphere shape of LS detectors with a radius of $17.7 \text{ m}$ in Fig. 5(a) where the $n_p$ in the detector is reduced to $0.725 \times 10^{33}$ ($\sim 10 \text{ kt}$) [23]. The expected event rate is obtained within the hemisphere shape of LS detectors with the cylindrical setup III $^8$Li generator. The evaluated event rates with $P_3$, $P_{3+1}$ and $P_{3+2}$, and their ratios are plotted in Fig. 5(b). The ratios of $R_{3+1}/R_3$ and $R_{3+2}/R_3$ turns out to be $\sim 0.955$ and $\sim 0.946$ regardless of $E_{\text{vis}}$, respectively. These energy independent features can provide interesting results for the existence of a hypothetical $\nu_s$.

The present proposed $\bar{\nu}_e$ source can also be useful for neutrino disappearance studies with future’s gigantic LS detectors (LSDs) such as LENA (Low Energy Neutrino Astronomy) [25]. A 50 kt LSD LENA type detector would have specific features of low energy detection threshold, good energy resolution, and particle identification with efficient background discrimination [49, 50, 51]. The fiducial volume size for LENA is
Table 1. The key parameters used in this work.

| Parameter                        | Value                                                                                  |
|----------------------------------|---------------------------------------------------------------------------------------|
| Neutron source                   | ²⁵²Cf                                                                                 |
| Neutron intensity                | $2.34 \times 10^{12}$ n/s/g                                                           |
| Neutrino production target       | ⁷Li (99.99% enhanced) surrounded by graphite                                          |
| Run period                       | 5 years                                                                                |
| $\bar{\nu}_e$ / neutron         | 0.256                                                                                 |
| $\bar{\nu}_e$ flux              | $6 \times 10^{11}$ $\bar{\nu}_e$/s/g                                               |
| Neutrino energy cut              | 7 MeV ($E_{\text{vis}} = 6.22$ MeV)                                                   |

| Detectors                        | hemisphere type                        | cylinder type                     |
|----------------------------------|----------------------------------------|----------------------------------|
| Fiducial mass                    | 10 kt                                  | 44 kt                            |
| IBD event total                  | 9750                                   | 4960                             |

set to be 14 m in the radius and 100 m in the height [49], and $3.3 \times 10^{33}$ target protons in the volume (44 kt) is assumed [25]. The ⁸Li generator is placed at this LS detector as shown in Fig. 6(a). The expected event rates are obtained within the cylinder shape of LS LENA type detectors, whose values with $P_3$, $P_{3+1}$ and $P_{3+2}$ and their ratios are plotted in Fig. 6(b). The ratios of $R_{3+1}/R_3$ are nearly constant with respect to $E_{\text{vis}}$. At the energies of $E_{\text{vis}} > 6$ MeV, however, the ratio of $R_{3+2}/R_3$ decreases as $E_{\text{vis}}$ increases. The comparison between the ratios of $R_{3+2}/R_3$ and $R_{3+1}/R_3$ in this $E_{\text{vis}}$ region can give a meaningful signal for distinguishing the 3+1 or 3+2 sterile neutrino scenarios. These characteristics are unique features of the present work due to the relatively higher energy of $\bar{\nu}_e$ ($E_{\bar{\nu}_e} < 13$ MeV) and the compact $\bar{\nu}_e$ source.

The 95% C.L. sensitivities of the hemisphere and the cylinder type detectors with the ⁸Li generator are obtained by following the Eq.(3) of Ref.[12] assuming 3% systematic uncertainty and 5% normalization uncertainty. The key parameters adopted for the sensitivity test are tabulated in Table 1 and whole results are plotted in Fig. 7, where we compared other sensitivities reported from Refs. [4, 10, 16]. For PROSPECT proposal [10], the High Flux Isotope Reactor (HFIR) [53] with a power of 85 MW and two neutrino detectors, AD-I and AD-II, were considered. And fiducialized target mass of 1.48 t ($\sim 7$ t) and baseline range of $7 \sim 12$ m ($15 \sim 19$ m) were assumed for AD-I (AD-II). The sensitivity of an accelerator-based IsoDAR by using ⁸Li source [16] was obtained by considering a proton accelerator with a power of 600 kW, a fiducial target mass of 897 t and 16 m distance between the target face and the center of the KamLAND detector [24]. Here we exploited the following 2-ν oscillation survival probability

$$P = 1 - \sin^2(2\theta_{\text{new}})\sin^2(1.27\frac{\Delta m_{\text{new}}^2[L/m]}{E[MeV]})$$

It is difficult to see the difference in Fig. 5(b) by the ¹⁴⁴Ce,¹⁴⁴Pr antineutrino generators [13, 14] due to the low energy of $\bar{\nu}_e$ ($E_{\bar{\nu}_e} < 3$ MeV).

+ The ⁸Li decays mainly to the broad 3.03 MeV, 2⁺ level (first-excited state) of ⁸Be, which then breaks up into two α particles [52]. Experimental ⁸Li yields can be obtained by measuring $\sim 3.03$ MeV of typical gamma-rays peaks from the ⁸Be* in the ⁸Li generator where the peak does not appear for the generator without Li.
where $\theta_{\text{new}}$ and $\Delta m^2_{\text{new}}$ are the new oscillation parameters. When a five-years run with 1.5 g of $^{252}$Cf is considered, the total expected events considering the effect of a half-life of $^{252}$Cf and the neutrino energy cut of 7 MeV with $P_3$ are 9750 and 4960 for the hemisphere and the cylinder type detectors, respectively. The results in Fig. 7 clearly show that the proposed neutrino source can cover the region in parameter space from the reactor anomalies for the two LS detectors, and thus our scheme can be effectively used for testing the $\nu_s$ hypothesis [4].

In summary, $\bar{\nu}_e$ source by the $^8\text{Li}$ generator with the neutron emitter $^{252}\text{Cf}$ is compact so that neutrino detectors can be placed within a few meters from this neutrino source with $E_{\bar{\nu}_e} < 13$ MeV. Therefore, it is an efficient neutrino source for the study of 1 eV mass scale $\nu_s$ as well as other neutrino oscillation study. Two different types of experiments are considered. One is the hemisphere type detector, where the $^8\text{Li}$ generator is placed at the center of the detector. Another is to place the generator at the cylinder type detector. The shapes of event rates in Figs. 5(b) and 6(b) for the hemisphere and the cylinder type detectors can give effective chances to search for the existence of $\nu_s$ and to test the 3+1 or 3+2 sterile neutrino scenarios. If we can measure higher than or equal to 5% deviation from the expected events, in the case that the $P_3$ model is true, we can conclude which of the $P_3$, $P_{3+1}$, and $P_{3+2}$ models is the most appropriate scenario. Together with the reactor anomaly, our electron-antineutrino source can also be used for a precise test of the weak mixing angle at $\Delta m^2 \sim 1 \text{ eV}^2$.
order scale relevant to the sterile neutrino as shown in the sensitivity test results in Fig. 7.

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