The potential to probe solar neutrino physics with LiCl water solution

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Abstract A solar neutrino detector relying on the charged-current (CC) interaction of $\nu_e$ on $^7\text{Li}$ is attractive. The total CC interaction cross-section weighted by the solar $^8\text{B}$ electron neutrino spectrum is approximately 60 times that of the neutrino-electron elastic scattering process. The final state effective kinetic energy after the CC interaction on $^7\text{Li}$ directly reflects the neutrino energy, which stands in sharp contrast to the plateau structure of recoil electrons of the elastic scattering. The recent measurement of the optical properties of saturated LiCl water solution, especially the long attenuation length, has once again aroused our interest in LiCl. In this work, with new B(GT) experimental measurements, the CC cross-section on $^7\text{Li}$ is reevaluated to be $3.759 \times 10^{-42}$ cm$^2$. Given the high solubility of LiCl of 74.5 g/100 g water at 10 $^\circ$C and the high natural abundance of 92.41% of $^7\text{Li}$, a solar neutrino detection proposal is made. The detector with high concentration LiCl water solution has a comparable CC event rate of $\nu_e$ on $^7\text{Li}$ with that of neutrino-electron elastic scattering. The contained $^{35}\text{Cl}$, $^6\text{Li}$, and H also make a delayed-coincidence detection for $\bar{\nu}_e$ possible. The advantages of studying the upturn effect of solar neutrino oscillation, light sterile neutrinos, and Earth matter effect are investigated in detail. The sensitivities in discovering solar neutrino upturn and light sterile neutrinos are presented.

The propagation of solar neutrinos has several special features under the standard MSW model [1,2]. At high energy, 5 MeV and above, the $\nu_e$ survival probability is low ($\sim$0.3) and dominated by the matter effect, while at low energy, 1 MeV and below, the probability is high ($\sim$0.5), and the flavor change occurs as in vacuum. Going from high to low energy, there is a smooth “upturn” of the survival probability. When arriving at the Earth, the neutrinos are decoherent mass eigenstates. The survival probability of $\nu_e$ arriving at a terrestrial experiment is further modulated according to their path in the Earth, and in the first order, it shows a day-night asymmetry. Both the Super-Kamiokande [3,4] and SNO’s [5] results favor an upturn. The Super-Kamiokande Earth matter effect search reaches 3 sigma significance. SNO also favors the Earth matter effects but with less significance. Therefore, further data would be helpful. In addition to confirming these theoretical predictions, future precise solar neutrino experiments [6–9] are expected to probe new physics. The weakly mixed light sterile neutrino model can influence the upturn curve of the $\nu_e$ survival probability and make it “dip and wiggle” in the expected upturn region [10,11]. Nonstandard interaction (NSI) [12], light dark matter [13], and neutrino decay [14] are also interesting solar neutrino physics topics to investigate.

The charged-current (CC) interaction of $\nu_e$ on nuclei is most favorable for such types of physics studies because the emitted electron energy is strongly correlated with the incident neutrino energy. In radiochemical neutrino experiments with the CC reactions, such as the Homestake experiment [15] with $^{37}\text{Cl}$, GALLEX/GNO [16,17], and SAGE [18] experiments with $^{71}\text{Ga}$, the energy of the electrons, however, is not measured. The SNO experiment [5] measured the solar neutrino oscillation with heavy water, and it is the only experiment to date to give a real-time energy measurement of the CC interactions on nuclei, i.e., deuterium. Other experimental attempts can also be found for $^{40}\text{Ar}$ [19,20],

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The feasibility of using lithium-7 as a target for neutrino detection was recognized in references [27–30] in the 1960s. Experimentally, researchers have proposed to detect the emitted electron signals in an electronic detector with a water solution of lithium chloride [31] or to extract the final state neutrino Cherenkov detector was stopped by a lack of optical transparency, especially in the UV. Instead, LiOH was suggested by Ref. [34], which is alkaline and has much less water-solubility than LiCl. The proposal of THIEA [8,35] and, by a solar angle cut, the interaction products of $\nu_e$ with $^7\text{Li}$ can be distinguished from the neutrino elastic scattering on electrons [5,35]. But the previous attempt by SUNLAB mentioned in Ref. [34] of using LiCl water solution for a solar neutrino Cherenkov detector was stopped by a lack of optical transparency, especially in the UV. Instead, LiOH was suggested by Ref. [34], which is alkaline and has much less water-solubility than LiCl. The proposal of THIEA [8,35] presented the expected event rates for lithium, as a function of energy, for a detector loaded with 10% $^7\text{Li}$ by mass.

The recent measurement of the optical properties of a saturated LiCl water solution, especially the long attenuation length of 50 m [36], has once again aroused our interest in LiCl. In this work, we discuss that the detection approach with LiCl water solution is practical and efficient for exploring energy-dependent solar neutrino physics. In Sect. 1, we present the detection channels of neutrinos in LiCl water solution and, in particular, the CC process on $^7\text{Li}$. We present a cross-section estimation of $\nu_e$ CC interaction $^7\text{Li}$ with new experimental transition matrix element inputs. In Sect. 2, we collect the properties of LiCl water solution and make a compact solar neutrino detection proposal with estimated detector performance. In Sect. 3, we clarify the advantage of LiCl water solution in measuring the solar neutrino upturn effect, the search for light sterile neutrinos, and the study of the Earth matter effect. The sensitivity of probing the upturn and sterile neutrinos with the detector proposal is presented in Sect. 4. The paper concludes in Sect. 5.

1 MeV neutrino detection in LiCl water solution

In this section, we introduce the detection channels of MeV neutrinos in LiCl water solution. The detection of $\nu_e$ is discussed first and then followed by the cross-section calculation of the CC interactions of $\nu_e$ on $^7\text{Li}$. The result is compared with the CC interactions of $\nu_x$ on $^{37}\text{Cl}$ and the elastic scattering of $\nu_x$ on electron, where $\nu_x$ represents $\nu_e$, $\nu_{\mu}$, and $\nu_{\tau}$. The $\bar{\nu}_x$ detection is discussed in the end.

1.1 Detection of neutrinos

The dominant interactions of neutrinos of 1–20 MeV in LiCl water solution are (1) the CC process of $\nu_e$ on $^7\text{Li}$ (LiCC), (2) the CC process of $\nu_e$ on $^{37}\text{Cl}$ (ClCC), (3) the neutral-current process of $\nu_x$ on $^7\text{Li}$ (LiNC), and (4) the elastic scatter of $e^-$ (ES).

The LiCC process, as shown in Fig. 1, is

$$\nu_e + ^7\text{Li} \rightarrow ^7\text{Be} + e^- (+\gamma).$$

(1)

The interaction can go through the ground state of $^7\text{Be}$ with a threshold of 0.862 MeV, in which both the Fermi and allowed Gamow–Teller (GT) transitions are possible [26,37]. The interaction can also go through the first excited state of $^7\text{Be}$ with a threshold of 1.291 MeV, producing an extra 0.429 MeV deexcitation $\gamma$, and the transition is also an allowed GT transition [26,37].

The neutrino energy threshold of the ClCC process is 0.814 MeV, which is very close to the LiCC threshold. More details of the ClCC process can be found elsewhere [38,39].

The LiNC process occurs as

$$\nu_x + ^7\text{Li} \rightarrow \nu_x + ^7\text{Li} + \gamma.$$  

(2)

The energy of the emitted $\gamma$ is 0.478 MeV [26,37]. Because it is very low and below the detection threshold of the hypothetical detector of this study, we skip the discussion involving the NC process in this paper.

The neutrino-electron elastic scattering is

$$\nu_x + e^- \rightarrow \nu_x + e^-,$$

(3)

which is an important solar neutrino detection channel [40].

The final state effective kinetic energy, $T$, of the LiCC process includes the final state $e^-$ and deexcitation $\gamma$ kinetic energy. It is calculated with the neutrino energy, $E_\nu$, as

$$T = E_\nu - 0.862 \text{ MeV}. $$

(4)

Similarly, the final state effective kinetic energy of the CICC process can be calculated as

$$T = E_\nu - 0.814 \text{ MeV}. $$

(5)

The $T$ of the CC processes represents the neutrino energy well, and this is critical for energy-dependent physics studies, such as the upturn, sterile neutrinos, and NSI effects.
Fig. 2 Distribution of the reconstructed solar angles, $\theta_{\odot}$, with $T > 5$ MeV. The distribution of $\nu_e$-elastic scattering is extracted from the Super-Kamiokande [42] and SNO+ [43] results. The distribution of $\nu_e^{-7}$Li and $\nu_e^{-37}$Cl CC processes is assumed to be uniform. The ratio of the number of CC events to that of ES events is set according to the last column of Table 3.

For the ES process in Eq. (3), the kinetic energy, $T$, of the recoil electron shows a plateau structure [41], which smooths out many energy-dependent features.

The angular distribution of the emitted electrons of the LiCC and CICC processes, as pointed out in [27,34,38], is slightly backwards with respect to the incident neutrino direction. With the contamination of the deexcitation gamma(s) of final states, the reconstructed direction distribution can be close to uniform in a real experiment. In contrast, the recoil electrons from the ES process favor the forward direction. Figure 2 shows the distribution of the reconstructed solar angle, $\theta_{\odot}$, which is the angle between the reconstructed final particle direction and the solar direction calculated with the position of the Sun. A uniform distribution is assumed for the CC processes, and a real distribution for the ES process is extracted from the Super-Kamiokande [42] and SNO+ results [43]. Their difference can be used to separate these two types of signals [5,35].

1.2 $^7$Li charged-current cross-section estimation

The LiCC cross-section, $\sigma$, for a specific $E_\nu$ and an energy level of $^7$Be is calculated according to [38,44-46]

$$\sigma = \sigma_0 \frac{\omega_e}{2\pi \alpha Z} F(\omega_e, Z),$$

(6)

where $\omega_e$ and $p_e$ are the electron energy and momentum in units of electron mass $m_e$, respectively, $\alpha$ is the fine structure constant, $Z$ is the atomic number of $^7$Be, $F(\omega_e, Z)$ is the Fermi function [45], and $\sigma_0$ is

$$\sigma_0 = \frac{2\alpha Z m_e^2}{\hbar^2} (G_V^2 \langle 1 \rangle^2 + G_A^2 \langle \sigma \rangle^2).$$

(7)

where $G_V$ and $G_A$ are the vector and axial coupling constants, respectively, and $\langle 1 \rangle$ and $\langle \sigma \rangle$ are the corresponding squares of the Fermi and Gamow–Teller transition matrix elements, represented by $B(F)$ and $B(GT)$ in experimental measurements. The $B(GT)$ values for the ground and first excited states are measured to be 1.19 and 1.06, respectively, with the ($^3$He,$t$) nuclear reaction [26,37]. The energy $\omega_e$ is determined by

$$\omega_e = \frac{E_\nu + [M(A, Z - 1) - M(A, Z)] + m_e - E_{ex}}{m_e},$$

(8)

which depends on $E_\nu, m_e$, the final atomic mass, $M(A, Z)$, the initial atomic mass, $M(A, Z - 1)$, and the average excitation energy of the final atom, $E_{ex}$ [44]. Then, the result is corrected for the screening effect of atomic electrons [45]. The cross-section is calculated for the $^7$Be ground state and the first excited state. The result as a function of $E_\nu$ is shown in Fig. 3, and the total cross-section weighted by an undistorted $^8$B spectrum [47] is $3.759 \times 10^{-42}$ cm$^2$. These quantities for the LiCC cross-section calculation are tabulated in Table 1.

Following the same calculation procedure and with the BT strength input from [39], the CICC process cross-section is repeated. The differential cross-section is shown in Fig. 3, and the total cross-section weighted by an undistorted $^8$B spectrum [47] is $1.069 \times 10^{-42}$ cm$^2$. The information is also tabulated in Table 1.

Our result for $^{37}$Cl is consistent with the result of $1.08 \times 10^{-42}$ cm$^2$ in [39] within 1%, where the same procedure and input parameters are taken. However, our new result for $^7$Li is about 7.5% higher than those calculated in [34] and the difference comes from B(GT) inputs and the normalization to
known mirror $\beta$-decay rates in Ref. [34]. The B(GT) inputs and LiCC cross-section from Ref. [34] are also shown in Table 1 for comparison. The $\nu_e - e$ and $\nu_{\mu,\tau} - e$ elastic cross-sections [41] are also shown in Fig. 3 and Table 1 for comparison. For the $^8\!\!B$ neutrinos, the LiCC cross-section is about 3.5 times that of the ClCC and about 60 times that of the ES process.

A thorough uncertainty analysis is not carried out here, but considering the neutrino-gallium flux calibration experiments [48,49], we think, in the future, a 2% uncertainty in the total CC cross-section from Ref. [34] are also shown for comparison. The total CC cross-section of $\nu_e$, $\nu_{\mu}$, and $\nu_{\tau}$, for the 8B neutrino spectrum [47]. The results from Ref. [34], we think, in the future, a 2% uncertainty in the total CC cross-section.

### 1.3 Detection of $\bar{\nu}_e$

LiCl water solution is also convenient for $\bar{\nu}_e$ detection, e.g. from geoneutrinos, and used as a multipurpose detector. The water solution contains many hydrogens, i.e., free protons, which are the target of the inverse-beta-decay process of $\bar{\nu}_e$,

$$\bar{\nu}_e + p \rightarrow n + e^+.$$  \hfill (9)

The neutron can be captured on $^6\!\!Li$ or $^{35}\!\!Cl$ or $^1\!\!H$ to form a delayed signal. The capture cross-section of reactor $\bar{\nu}_e$ are $940 \times 10^{-24}$ cm$^2$, $44 \times 10^{-24}$ cm$^2$, and $0.3 \times 10^{-24}$ cm$^2$ for $^6\!\!Li$, $^{35}\!\!Cl$, and $^1\!\!H$, respectively. The delayed signals are dominantly a triton and an $\alpha$ for the capture on $^6\!\!Li$ [50] or several gammas with a total energy of 8.6 MeV for the capture on $^{35}\!\!Cl$ [5], or a 2.2 MeV gamma for $^1\!\!H$ [51]. With the natural abundance input of the Li and Cl isotopes, the neutron capture probability on $^6\!\!Li$ is about 66%, the capture probability on $^{35}\!\!Cl$ is about 32%, and 2% on $^1\!\!H$. The delayed coincidence is excellent in extracting the $\bar{\nu}_e$ signals and suppressing backgrounds. The triton and $\alpha$ from neutron capture on $^6\!\!Li$ are below the Cherenkov threshold in water, and scintillator light is required to detect them.

### 2 Detector with LiCl water solution

In this section, we report the $^7\!\!Li$, $^{37}\!\!Cl$, and electron molarities in LiCl water solution and the related LiCl purification and properties. Then, we present a compact detector setup and the corresponding properties, such as the energy resolution, angular resolution, vertex resolution, detection threshold, and fiducial volume. The primary experimental location is the China Jinping Underground Laboratory (CJPL), where the cosmogenic background is low.

#### 2.1 $^7\!\!Li$, $^{37}\!\!Cl$, and electron molarities in LiCl water solution

A LiCl water solution with high $^7\!\!Li$ molarity can be easily achieved at room temperature. The density of a saturated LiCl water solution at room temperature is measured to be about 1.2 g/cm$^3$. The solubility of LiCl in water is rather high, i.e., 74.5 g/100 g water at 10 °C, and Table 2 shows the solubility at several temperatures [52]. The natural abundance of $^7\!\!Li$ is 92.41% [53], and the natural abundance of $^{37}\!\!Cl$ is only 24.24%. In a saturated LiCl water solution at 10 °C, the molarities of $^7\!\!Li$, $^{37}\!\!Cl$, and electron are 11, 2.9, and 610 mol/L, respectively, as shown in Table 3.

#### 2.2 LiCl purification

For the application in a neutrino detector, the purification of LiCl is a key question. For a market sample, usually with a purity of $\geq 99\%$, after it is dissolved in 18 MΩ cm$^{-1}$ pure water, filtration with a 0.1 μm membrane is the first essential procedure to remove the dominant impurity. Powdered activated carbon of 200 mesh is added to the solution for the absorption of impurities less than 0.1 μm. Then the solution pass through a 0.1 μm membrane again to remove the carbon powder. Observing that the solubility of LiCl in water varies with temperature as shown in Table 2, we find that LiCl can be thermally recrystallized. The saturated solution after acti-

### Table 1

| Channel | $E_l$ (MeV) | B(GT) | B(F) | $\sigma$(B) (10$^{-42}$ cm$^2$) |
|---------|-------------|-------|------|------------------------------|
| $^7\!\!Li$ gs.-gs. | 0 | 1.19 | 1.00 | 2.470 |
| $^7\!\!Li$ gs.-ex. | 0.429 | 1.06 | 1.289 |
| $^7\!\!Li$ total | 3.759 | |
| $^7\!\!Li$ gs.-gs. [34] | 0 | 1.747 | 1.00 | 2.299 |
| $^7\!\!Li$ gs.-ex. [34] | 0.429 | 1.630 | 1.198 |
| $^7\!\!Li$ total [34] | 3.497 | |
| $^{35}\!\!Cl$ total | 1.069 | |
| $e^-$ | | | | 0.061 |

### Table 2

| Temperature (°C) | Solubility (g/100 g water) | $^7\!\!Li$ mass fraction (%) |
|------------------|-----------------------------|------------------------------|
| 0                | 68.3                        | 6.21                         |
| 10               | 74.5                        | 6.53                         |
| 20               | 83.2                        | 6.95                         |
| 40               | 89.4                        | 7.22                         |
| 60               | 98.8                        | 7.60                         |
| 80               | 112.3                       | 8.09                         |
additional input of the UV absorption spectrum result, the ±430 nm with an FWHM of 14 nm. The attenuation length of >10 cm. The event rates for the charged-current interactions of νe on 7Li, 37Cl, and the elastic scatterings of νe on e− are also shown, where they are calculated with the undistorted 8B νe spectrum [47], oscillated spectrum, and oscillated spectrum plus a T > 4 MeV or T > 5 MeV cut. All the rows for event rates are in the units of 1/100 ton-year.

| Molarity (mol/L) | 7Li | 37Cl | All CC | e− |
|------------------|-----|------|--------|----|
| Event rate (No Osci) | 349 | 26 | 375 | 310 |
| Event rate (Osci | 119 | 8.5 | 127 | 143 |
| Event rate (Osci & >4 MeV) | 111 | 8.5 | 119 | 56 |
| Event rate (Osci & >5 MeV) | 102 | 8.4 | 110 | 40 |

Carbostyril 124 is a wavelength shifter previously investigated in Ref. [55]. For a detector with a diameter larger than ten meters, short-wavelength Cherenkov light in the UV range will be absorbed quickly and will not contribute to the final light yield. These lights, however, can be converted to longer wavelengths and emitted isotropically, like scintillation, to enhance the light yield. By controlling the amount of Cherenkov light and shifted light, i.e., maintaining the dominance of Cherenkov light, the position, energy, and direction can all be well reconstructed [56]. In Ref. [36], 1 ppm of carbostyril 124 is successfully added to a saturated LiCl aqueous solution. The Cherenkov and shifted light emissions are also verified.

2.5 Neutrino detector proposal and property

We consider an experiment at the CJPL with LiCl water solution in this work. The structure of the detector is similar to the SNO (SNO+) experiment [5]. A sketch of the detector is shown in Fig. 4. From outside to inside, it consists of a muon veto region, water buffer region, and central target region. The muon veto region is filled with water and is equipped with photomultipliers (PMTs) to veto cosmic-ray muons and shield radioactive backgrounds. The spherical water buffer region further shields the radiative background from outside and is instrumented with about tens of thousands of 8-inch PMTs to detect the optical photon signals from the central target region. The central target region is enclosed in a spherical acrylic vessel and filled with LiCl solution. The diameter of the water buffer volume is 16 m. The diameter of the acrylic vessel is 14 m, which matches the measured attenuation length, and the thickness of the acrylic vessel is about 5 cm. To run the detector safely at 20°C, we assume that the LiCl concentration is 78.8 g/100 g water, i.e., the saturated level of 15°C to avoid precipitation (see the discussion in Sect. 2.1). The total PMT photocathode coverage is about 50% and the PMT photon detection efficiency (quantum efficiency times collection efficiency) is 30%. The transition time spread is about 1.5 ns for effective reconstruction of the Cherenkov light. Further optimization must be done in the future for a real experiment. Note that LiCl water solution is corrosive to metal. Glass, acrylic, Teflon, or Teflon-lined containers or tools are necessary. In this work, we focus on the neutrino signals from 8B neutrinos.

The publications of SNO, SNO+ [5, 43] and Super-Kamiokande [3] experiments show their energy resolution,
angular resolution, vertex resolution, fiducial volume, and detection threshold. A full detector simulation is also built, taking into account the LiCl attenuation length and UV–Vis spectrum measurement, and a complete likelihood reconstruction is performed based on the full simulation [56]. The experience from other experiments and our results are discussed below.

The Cherenkov light signals from charged particles are detected with the PMTs. The energy resolution for particles follows the Poisson uncertainty of the total number of detected photoelectrons (PEs). With the assumed photocathode coverage and PMT photon detection efficiency, our full simulation work shows a light yield of greater than 10 PE/MeV expected, which is consistent with the SK and SNO results.

Direction reconstruction is performed with the Cherenkov light. A resolution of about 35 degrees (68% C.L.) has been achieved for electrons with energy greater than 5 MeV at the SNO and Super-Kamiokande experiments [3,5] and our full detector simulation work presents a consistent angular resolution. The energy-dependent resolution distributions from the Super-Kamiokande experiment are extracted and used in this study.

The event vertex can be reconstructed with the Cherenkov light. Experience from Super-Kamiokande and our full detector simulation work indicates that a resolution better than one meter is expected.

To reduce the radiative background from PMTs and detector structures, only a central fiducial volume is available for physics studies. Because we focus on signals with energy greater than 5 MeV, the central spherical volume with a 10.1 m diameter is considered the fiducial volume for the proposed 14-m diameter acrylic vessel. The fiducial region is 540 m$^3$ or 640 tons. The total amount of $^7$Li in the fiducial volume is $5.90 \times 10^6$ moles or 41.2 tons.

For the expected CJPL site, a 5 MeV detection threshold is realistic for a background-free solar neutrino study, as shown in the SNO+ result [43]. We are also interested in a water-based liquid scintillator [35,54,57] in which the scintillation light yield is comparable with Cherenkov light. This will further enhance the light yield and energy resolution and maintain a similar performance for the direction reconstruction [56,58]. The solution with the carboystyrl 124 component [36] is an initial effort in this direction. Given that a better energy resolution is expected to suppress low-energy radioactive or instrumental background, an optimistic 4 MeV threshold is also tested below for a few studies. More work to reach the 4 MeV threshold is required.

3 Advantage of solar neutrino physics study

In this section, we demonstrate that the LiCl-based detection strategy has advantages for energy-dependent neutrino physics studies. The candidate event rates and spectra of the LiCC, CICC, and ES processes are explained first, and then we look at the solar neutrino upturn issue, the light sterile neutrino search, and the Earth effect.

3.1 Candidate event rates

We focus on the $^8$B neutrino studies with both 4 and 5 MeV detection thresholds as explained in Sect. 2.5. In this work, the total $^8$B flux is assumed to be $5.25 \times 10^6/(\text{cm}^2\text{s})$ as measured by the SNO experiment [5]. We adopt the $^8$B neutrino spectrum prediction, $\Phi_\nu(E_\nu)$, in [47], which is shown in Fig. 5.

The differential energy spectra of all neutrino flavors at a terrestrial detector are evaluated numerically. The calculation starts with the generation of $^8$B neutrinos according to their spatial probability density function [59]. Then, their propagation and oscillation probability is estimated. Their survival or appearance probability of $\nu_e$, $\nu_\mu$, and $\nu_\tau$ at a terrestrial detector is represented by $P_{ee}(E_\nu)$, $P_{\mu\mu}(E_\nu)$, and $P_{\tau\tau}(E_\nu)$, respectively. The numerical calculation methods for the three-active-neutrino propagation in the Sun, the case with one sterile neutrino (3+1), and the neutrino propagation in the Earth are not identical. Next, the three-active-neutrino propagation in the Sun is introduced first. More detailed explanations for the (3+1) case and the propagation in the Earth are given in the relevant sections.

For the three-active-neutrino propagation in the Sun, the following calculation is carried out according to the MSW theory. The $^8$B neutrino generation zone ($r < 0.135R_\odot$, where $R_\odot$ is the radius of the Sun) is divided into 60 shells.
Neutrinos are generated according to the predicted probability density in each shell [59]. The initial $v_e$ flux is decomposed into mass eigenstates $v_1$, $v_2$, and $v_3$ according to the local number density of electrons [59]. With the adiabatic assumption [1,2], these mass eigenstates are propagated outside until vacuum density is reached. The neutrino oscillation parameters used are $\theta_{12} = 0.587$ [3], $\theta_{13} = 0.148$ [60], $\theta_{23} = 0.849$ [61], $\Delta m^2_{21} = 7.49 \times 10^{-5}$ eV$^2$ [3], $\Delta m^2_{31} = 2.53 \times 10^{-3}$ eV$^2$ [61]. The oscillated $^8$B neutrino energy spectrum and $P_{ee}(E_\nu)$ are also shown in Fig. 5.

The neutrino event rates and spectra of LiCC and CICC are estimated according to the cross-sections and the molarities of $^7$Li and $^{37}$Cl in the LiCl solution. The event rate, $N_{\text{LiCC}}$, as a function of the kinetic energy (defined in Eq. (4)) is calculated as

$$N_{\text{LiCC}}(T) = t N_{\text{Li}} \sum_{i} \Phi_\nu(E_\nu) \sigma_{\nu_i,\text{Li}}(E_\nu, T) P_{ee}(E_\nu),$$  \hspace{1cm} (10)$$

where $\sigma_{\nu_i,\text{Li}}(E_\nu, T)$ is calculated in Eqs. (4), (6), (7), and (8), including all final state levels of $^7$Be, $t$ is the data-taking time, and $N_{\text{Li}}$ is the number of target $^7$Li per unit LiCl water solution as described in Sect. 2.5. Similarly, we obtain the event rate and spectrum, $N_{\text{CICC}}(T)$, for the CICC process.

The energy spectrum of all CC events on nuclei is

$$N_{\text{CC}}(T) = N_{\text{LiCC}}(T) + N_{\text{ClCC}}(T).$$  \hspace{1cm} (11)$$

Both the oscillated and undistorted $T$ spectra of $^8$B neutrino CC events are shown in Fig. 6. The integrated LiCC, CICC, and all CC rates with undistorted $^8$B neutrino spectrum, oscillated spectrum, and oscillated spectrum plus a $T > 4$ MeV or $T > 5$ MeV cut are calculated and tabulated in Table 3. The CICC event rate is 7% of the LiCC process.

All $v_e$, $v_\mu$, and $v_\tau$ scatter on electrons. The kinetic energy spectrum, $N_{\text{ES}}(T)$, of recoil electrons contains all three contributions, and it is

$$N_{\text{ES}}(T) = t N_e \int dE_\nu \Phi_\nu(E_\nu) \left\{ \sigma_{\nu_e}(E_\nu, T) P_{ee}(E_\nu) + \sigma_{\nu_\mu,\tau}(E_\nu, T) \left[ 1 - P_{ee}(E_\nu) \right] \right\},$$  \hspace{1cm} (12)$$

where $\sigma_{\nu_e}(E_\nu, T)$ and $\sigma_{\nu_\mu,\tau}(E_\nu, T)$ are the differential scattering cross sections as a function of electron kinetic energy for $v_e$ and $v_{\mu,\tau}$ [41], respectively, and $N_e$ is the total number of target electrons per unit LiCl water solution as described in Sect. 2.5. Both the oscillated and undistorted $T$ spectra of the $^8$B neutrinos of the ES process are shown in Fig. 7.

Fig. 5 Solar $^8$B electron neutrino energy spectrum with different oscillation configurations (upper panel) and their corresponding survival probability curves (lower panel). For the sterile neutrino mixing, $\alpha = 0.021$ and $\Delta m^2_{\nu_1} = 1.56 \times 10^{-5}$ eV$^2$.

Fig. 6 The final state effective kinetic energy spectra of the LiCC and CICC signal events of $^8$B neutrinos with different oscillation configurations (upper panel) and the ratios of the oscillated spectra to the undisturbed spectrum (lower panel). For the sterile neutrino mixing, $\alpha = 0.021$ and $\Delta m^2_{\nu_1} = 1.56 \times 10^{-5}$ eV$^2$. The exposure is set to 100-ton LiCl solution $\times$ 1 data-taking year, and the LiCl concentration in the water solution is assumed to be 78.8 g/100 g water.
The integrated ES event rates with the undistorted $^8$B neutrino spectrum, oscillated spectrum, and oscillated spectrum plus a $T > 4$ MeV or $T > 5$ MeV cut are calculated and tabulated in Table 3. The ratio of the CC event rate to that of ES events is 127:143 for the oscillated spectrum, and it is further enhanced to 110:40 with the $T > 5$ MeV cut. In Fig. 2, correspondingly, the ratio of the number of CC events to the number of ES events is set according to 110:40.

In summary, as seen in Table 3, the total event rates of CC, mainly LiCC, and ES are comparable in the proposed LiCl water solution. With a $T > 4$ MeV or $T > 5$ MeV cut, the CC events are dominant.

### 3.2 Upturn effect

In the following discussion, we compare the signal strengths of the upturn effect of the CC and ES processes.

In Fig. 5 of the $P_{ee}(E_v)$ of the MSW solution, a clear upturn can be seen from the high energy to low energy. As a reference, a flat survival probability $P_{ee}$ is plotted in Fig. 5, in which $P_{ee}$ is set to a constant of 0.31, and $P_{e\mu} + P_{e\tau} = 0.69$.

With the CC interactions on $^7$Li or $^{37}$Cl, the final state effective kinetic energy spectrum is calculated with Eq. (11) and shown in Fig. 6. We define $R_{CC}(T)$ as

$$R_{CC}(T) = \frac{N_{CC}(T) | \text{Osci} \rangle}{N_{CC}(T) | \text{No Osci} \rangle}$$

(13)

which is the ratio of the kinetic energy spectra under the oscillation condition (Osci) to no oscillation (No Osci). The spectrum of $R_{CC}(T)$ is plotted in the lower panel of Fig. 6. This CC channel result has a consistent signal strength with the original MSW result.

For the ES process, the kinetic energy spectrum of the recoil electron is calculated according to Eq. (12) and shown in Fig. 7. A similar ratio of $R_{ES}(T)$ is defined as

$$R_{ES}(T) = \frac{N_{ES}(T) | \text{Osci} \rangle}{N_{ES}(T) | \text{No Osci} \rangle},$$

(14)

which is the ratio of the oscillated kinetic energy spectrum to the undistorted spectrum. The spectrum of $R_{ES}(T)$ is plotted in the lower panel of Fig. 7. However, we notice that in the ES process, even for the flat survival probability, there is a minor upturn in the ratio plot, which is shown in the lower panel of Fig. 7. This is caused by the difference in the differential cross-section in $\nu_e$-$e$ and $\nu_{\mu,\tau}$-$e$. An extra $\nu_{\mu,\tau}$ contribution appears to the low energy part of the recoil electron spectrum.

In summary, in such a LiCl detector, as described in Sect. 2, the strength of the upturn signal of the CC processes on LiCl is much larger than that of the ES process.

### 3.3 Sterile neutrino

The neutrino transition probability $P_{ee}(E_v)$, $P_{e\mu}(E_v)$, and $P_{e\tau}(E_v)$ calculation with the (3+1) situation [10,11] is done in the following way.

We adopt the parameter convention of sterile neutrinos in [10,11]. One parameter, mixing angle $\alpha$, describes the mixing between the sterile neutrino, $\nu_s$, and active neutrinos, and the other parameter, mass squared difference $\Delta m_{01}^2$, is the mass squared difference between $\nu_0$ and $\nu_1$, in which $\nu_0$ is introduced along with $\nu_s$. With a small mixing angle $\alpha$, $\nu_s$ mixes weakly with active neutrinos, and $\nu_s$ almost coincides with $\nu_0$.

The nonadiabatic situation must be considered for the propagation of (3+1) neutrinos in the Sun for some parameter settings of $\alpha$ and $\Delta m_{01}^2$. In the numerical calculation, the $^8$B neutrino are generated in a cube at the solar center with a side length of 0.135 $R_\odot$ since the $^8$B neutrinos are dominantly generated in the $r < 0.135 R_\odot$ region [59]. The cube is sliced into $60 \times 60 \times 60$ ($x \times y \times z$) small cells, and $^8$B neutrinos are generated according to the probability density function [59]. The slicing scheme is a balance of pre-
cision and computer calculation time. We use two different numerical methods to calculate the flavor transition probability $P_{\nu e}(E_\nu)$, $P_{\nu e\mu}(E_\nu)$, and $P_{\nu e\tau}(E_\nu)$. One is the multislab method. The neutrino outgoing path is divided into many slabs with a step size of $R_\odot/1000$. Besides the local number density of electrons, the local number density of neutrons [59] is also considered for the important neutral current process [10,11]. Each slab is assumed to have a uniform material with a constant number density. Flavor and mass eigenstate transfer occurs at each slab interface. The other method is a 4th-order Runge–Kutta method, which is used to solve the propagation differential equations with $10^6$ steps. The probabilities $P_{ee}(E_\nu)$, $P_{e\mu}(E_\nu)$, and $P_{e\tau}(E_\nu)$ calculated by the two methods are in good agreement in our test, as in [62]. The multislab method is easier and faster to obtain a stable solution for this calculation. No Earth matter effect is considered since the difference introduced by the Earth effect is not significant for this study [63].

Taking one set of sterile neutrino mixing parameters ($\alpha = 0.021$ and $\Delta m^2_{01} = -1.56 \times 10^{-5}$ eV$^2$) as an example, the oscillated neutrino spectrum and the $\nu_e$ survival probability $P_{ee}(E_\nu)$ are shown in Fig. 5. The kinetic energy spectrum of the CC processes and its ratio to the undistorted spectrum are both shown in Fig. 6. The recoil electron kinetic energy spectrum of the ES process and its ratio to the undistorted spectrum are both shown in Fig. 7.

With these comparisons, we see that the rich structure information in Fig. 5 is preserved in the CC process, as shown in Fig. 6; however, it is almost smeared out in Fig. 7 with the ES process. To distinguish the sterile neutrinos with the CC channels, fewer signal statistics are needed.

### 3.4 Earth matter effect

In this section, we follow the three-active-neutrino oscillation calculation in Sect. 3 and then continue with the oscillation calculation of the Earth matter effect. A multilayer Earth model [64] is adopted, and a multislab numerical calculation (Sect. 3.3) is implemented.

In the upper panel of Fig. 8, the $\nu_e$ survival probability $P_{ee}$ is shown as a function of the neutrino energy, $E_\nu$, and zenith angle of solar neutrinos, $\cos(\theta_z)$ determined by the detection time, i.e. the relative position of the Sun and the Earth. For the neutrino going through the Earth, $\cos(\theta_z)$ is negative. The $0 > \cos(\theta_z) > -0.84$ region is for neutrinos going through the Earth mantle and $-0.84 > \cos(\theta_z) > -1$ is for the Earth core. In the mantle region, many radial yellow lines are visible, and each of them corresponds to a roughly constant $\cos(\theta_z)/E_\nu$, i.e. $L/E_\nu$, where $L$ is the neutrino path length. When neutrinos pass the Earth core, the core density significantly increases compared to the mantle density, and a more complicated structure can be found. More details can be found in Ref. [65].

With the CC processes on LiCl, the kinetic energy spectrum is obtained for each solar angle as done with Eq. (11). In the middle panel of Fig. 8, we show the $R_{CC}$ (defined in Eq. (13)) as a function of the kinetic energy, $T$, and $\cos(\theta_\odot)$. The lower panel of Fig. 8 is the plot for $R_{ES}$ (defined in Eq. (14)) for the ES process.

First, the original rich pattern in the neutrino plot (upper panel of Fig. 8) is well repeated in the LiCl CC plot (middle panel) but is almost smeared out in the ES plot (lower panel). Second, the structures are mostly seen in the 4–12 MeV region of the neutrino plot (upper and middle panels), where the CC kinetic energy spectrum has the most statistics, as seen in Fig. 6. There are some residual structures in the ES plot higher than 10 MeV (lower panel), but the statistics of the ES signals is low, as seen in Fig. 7. In conclusion, the CC
process is most helpful in distinguishing the Earth matter effect.

4 Sensitivity study for upturn and sterile neutrino

In this section, more realistic detector effects and signal selection criteria are considered. The sensitivity of the upturn study and sterile neutrino search is presented. The Earth matter effect study for the fine structures in Fig. 8 requires a different detector setup, such as a scintillation detector with a few hundred PE/MeV light yield and much more exposure, and this subject cannot be fulfilled in this 640-ton detector and will be studied in the future.

4.1 Detector effects and signal selection criteria

With the detector proposal and expected property described in Sect. 2.5, more realistic predictions are made, and based on the predictions, many random samples are generated for the following sensitivity studies.

A gauss energy smearing with an energy resolution of 10 PE/MeV (Sect. 2), \( R(T, E_{\text{rec}}) \), is applied to the kinetic energy spectrum of \( N_{\text{CC}}(T) \) (Eq. 11) and \( N_{\text{ES}}(T) \) (Eq. 12).

\[
N_{\text{CC}}(E_{\text{rec}}) = N_{\text{CC}}(T) \otimes R(T, E_{\text{rec}}),
\]

\[
N_{\text{ES}}(E_{\text{rec}}) = N_{\text{ES}}(T) \otimes R(T, E_{\text{rec}}),
\]

(15)

where \( E_{\text{rec}} \) is the reconstructed energy, and the corresponding energy spectra \( N_{\text{CC}}(E_{\text{rec}}) \) and \( N_{\text{ES}}(E_{\text{rec}}) \) are obtained for the CC and ES processes, respectively. For the limited data-taking time and target mass and a binned fitting later, each \( E_{\text{rec}} \) spectrum is divided into several 1 MeV bins, and the bin content in each bin is denoted with \( N_{\text{CC},i} \) or \( N_{\text{ES},i} \), where \( i \) is the bin number.

The CC and ES events are the background to each other. As discussed in Sect. 2.5, the SNO+ [43] result shows a very low background, close to zero, above a 5 MeV threshold. We assume that there is no other background with an \( E_{\text{rec}} \geq 5 \) MeV cut or a more aggressive \( E_{\text{rec}} \geq 4 \) MeV cut. To realize the \( E_{\text{rec}} \geq 4 \) MeV cut, more work on background suppression is needed.

The ES and CC signals must be separated with a reconstructed solar angle cut (see Fig. 2). Applying a solar angle cut at 60 degrees, i.e., \( \cos(\theta_{\text{Sun}}) = 0.5 \), a CC-rich sample with 75% of the CC events and a small fraction of the ES events and an ES-rich sample with 25% of the CC events and a large fraction of the ES events are obtained. They are represented by

\[
N_{\text{CC-rich},i} = N_{\text{CC},i}75\% + N_{\text{ES},i} \epsilon_{\gamma},
\]

\[
N_{\text{ES-rich},i} = N_{\text{CC},i}25\% + N_{\text{ES},i}(1 - \epsilon_{\gamma}),
\]

(16)

where the energy-dependent ES selection efficiency, \( \epsilon_{\gamma} \), is read off from the Super-Kamiokande publication [3] and used throughout the paper. On average, \( \epsilon_{\gamma} \) is approximately 10%. The predicted \( N_{\text{CC-rich},i} \) and \( N_{\text{ES-rich},i} \) are shown in Fig. 9, and the LiCC, CICC, and ES components are also shown.

4.2 Upturn effect

Poisson random sampling is performed according to the predictions in Eq. (16). A total of 1000 random samples are generated, and for each sample, there are two sub datasets, \( D_{\text{CC-rich},i} \) and \( D_{\text{ES-rich},i} \), for the CC-rich and ES-rich, respectively.

Each random sample is fitted with the following \( \chi^2 \)

\[
\chi^2 = \sum_{i} (D_{\text{CC-rich},i} - P_{\text{CC-rich},i})^2 / D_{\text{CC-rich},i}
+ \sum_{i} (D_{\text{ES-rich},i} - P_{\text{ES-rich},i})^2 / D_{\text{ES-rich},i}
+ \text{Pull},
\]

(17)
tainties as below for the fit.

\[
P_{\text{CC-rich}, i} = [N_{\text{CC}}, 75\%(1 + \eta_\sigma) + N_{\text{ES}, i}\epsilon_r(1 + \eta_\epsilon)] \\
\quad \times (1 + \eta_{\text{Norm}}),
\]

\[
P_{\text{ES-rich}, i} = [N_{\text{CC}}, 25\%(1 + \eta_\sigma) + N_{\text{ES}, i}(1 - \epsilon_r(1 + \eta_\epsilon))] \\
\quad \times (1 + \eta_{\text{Norm}}).
\]

(18)

where the LiCC cross-section uncertainty, \(\eta_\sigma\), the selection efficiency uncertainty of the ES process, \(\eta_\epsilon\), and the normalization uncertainty, \(\eta_{\text{Norm}}\) are taken into account. The \(^{8}\)B neutrino spectrum theoretical error in the energy region of interest [66] is very small compared to the expected statistical error, and the theoretical spectrum uncertainty is ignored in this study. The uncertainty of the LiCC cross-section is the topic of this paper. To focus on the upturn issue, the interest [66] is very small compared to the expected statistical uncertainty includes the impact of the high-low metallicity ambiguity [67] and fiducial mass and is assigned as 10%. The fit basically only considers the shape of the observed spectrum. Correspondingly, the pull term is

\[
\text{Pull} = (\eta_\sigma/2\%)^2 + (\eta_\epsilon/10\%)^2 + (\eta_{\text{Norm}}/10\%)^2.
\]

(19)

For the upturn study, we adopt two kinds of simplified \(P_{ee}(E_\nu)\) for Eq. (18). The first one is a quadratic function of \(E_\nu\) as used in the SNO [5] and Super-Kamiokande [3] experiments. Using the 10 MeV survival probability as the reference point, the survival probability is

\[
P_{ee}(E_\nu) = c_0 + c_1(E_\nu - 10) + c_2(E_\nu - 10)^2.
\]

(20)

All \(c_0, c_1,\) and \(c_2\) are fitted simultaneously. The term \(c_0\) is for the average survival probability at 10 MeV, which is not the topic of this paper. To focus on the upturn issue, the best fit and rms spread of \(c_1(E_\nu - 10) + c_2(E_\nu - 10)^2\) for the LiCl water solution detector with the exposure of 6400 ton-year are shown in Fig. 10, where both the 5 MeV cut and 4 MeV cut results are analyzed. With a lower detection threshold, a better sensitivity is achieved at low energy. The result from the SNO experiment is also overlaid for comparison. A significant improvement with the compact LiCl detector can be expected. Note that the linear function is only a good approximation for the MSW effect and the sensitivity to MSW distortion might be slightly different.

The sensitivity of observing the upturn is scanned with exposures of 640 tons \(\times 1, 3, 5, 7.5, \) and 10 years. One thousand data samples are generated with each exposure setting. Because of the joint contribution of \(c_1\) and \(c_2\), the upward or downward slope is difficult to quantify. The \(P_{ee}(E_\nu)\) in Eq. (20) is replaced by a simple linear function as below

\[
P_{ee}(E_\nu) = c_0 + c_1(E_\nu - 10).
\]

(21)

If a statistically significant negative fit result of \(c_1\) is obtained, an upturn is observed. On the contrary, a zero or positive fit result of \(c_1\) corresponds to no upturn effect, i.e., the null assumption. The 1000 \(c_1\) fit results of each exposure setting are plotted. They are gauss distributed, and the mean \(\mu_{c_1}\) and resolution \(\sigma_{c_1}\) are obtained. For our proposed detector setup and exposures, \(\mu_{c_1}\) is always negative, i.e., the upturn is favored. The sensitivity, \(S\), is calculated by \(S = \int_{-\infty}^{0} \text{Gaus}(\mu_{c_1}, \sigma_{c_1})\). The sensitivity with the 5 MeV and 4 MeV cuts versus the exposures is shown in Fig. 11, where 3\(\sigma\) corresponds to \(S=97.73\%\). The required exposure is much smaller than the SNO and Super Kamiokande experiments.
5 Conclusion and discussion

After knowing the 50 m long attenuation length of saturated LiCl water solution, we studied the MeV neutrino detection in LiCl water solution. We reevaluated the $\nu_e$ charged-current interaction cross-section on $^7\text{Li}$ with new B(GT) experimental inputs. The total CC interaction cross-section weighted by the solar $^8\text{B}$ electron neutrino spectrum is $3.759 \times 10^{-42} \text{ cm}^2$, which is about 60 times the neutrino-electron elastic scattering process. In addition, $^{37}\text{Cl}$ also contributes about seven percent to the CC event rate. The contained $^{35}\text{Cl}$, $^6\text{Li}$, and $^7\text{Li}$ also make the delay-coincidence detection for electron antineutrinos possible. The detector with LiCl water solution is basically a MeV-scale $\nu_e$ and $\bar{\nu}_e$ spectrometer.

We investigated the physical properties of LiCl and its water solution. A very high molarity of $^7\text{Li}$ of 11 mol/L can be achieved for operations at room temperature. The event rate of $\nu_e$ on $^7\text{Li}$ in a LiCl water solution is comparable to the elastic scattering. An experimental proposal is made. The energy and angular resolutions are estimated. The CC signals can be well separated from the elastic signals by a solar angle cut. The sensitivities in studying the solar neutrino upturn and light sterile neutrinos are reported for the proposed experiment, and the sensitivities are much better than the SNO and Super Kamiokande experiments.

To achieve the detection of solar neutrinos, the radioactive background is an important issue to investigate and is the next step of this study.

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In summary, we expect an improvement in studying the upturn effect with the LiCl water solution detector.

4.3 Sterile neutrino

We use the Feldman–Cousin method [68] to determine the exclusion sensitivity [69] of a detector with the exposure of 6400 ton-year. The $\alpha$ and $\Delta m^2_{01}$ parameter space, $\log_{10}(\sin^2 2\alpha) \in [-5, -2]$ and $\Delta m^2_{01} \in [0, 25 \times 10^{-6}] \text{ eV}^2$, is split into $40 \times 40$ grids. For each grid, 500 statistically random samples are generated according to the exposure configuration. The $P_{ee}(E_e)$ calculation procedure is described in Sect. 3.3, and the detector effect is added as in Eqs. (15) and (16) of Sect. 4.1. With the $\chi^2$ definition in Eqs. (17), (18) and (19), the exclusion sensitivity is estimated. Figure 12 shows the sensitivity contours with a 5 MeV cut. Besides the statistical power, the proposed detector and settings are not sensitive to some sterile parameter regions due to the 5 MeV cut and the systematic uncertainties.

![Fig. 11](image1.png)  The sensitivity of rejecting no upturn effect versus the exposure. More detector resolution and signal selection information can be seen in Sect. 4.1

![Fig. 12](image2.png)  Exclusion sensitivity of sterile neutrinos using a LiCl detector with an exposure of 6400 ton-year. More detector resolution and signal selection information can be seen in Sect. 4.1

The sensitivity of rejecting no upturn effect versus the exposure. More detector resolution and signal selection information can be seen in Sect. 4.1.
References

1. L. Wolfenstein, Neutrino oscillations in matter. Phys. Rev. D 17, 2369 (1978)
2. S.P. Mikheyev, A.Y. Smirnov, Resonance amplification of oscillations in matter and spectroscopy of solar neutrinos. Sov. J. Nucl. Phys. 42, 913 (1985)
3. K. Abe et al., Solar neutrino measurements in Super-Kamiokande-IV. Phys. Rev. D 94(5), 052010 (2016)
4. Recent results and future prospects from Super-Kamiokande, Presentation at the Neutrino 2020 conference
5. B. Aharmim et al., Combined analysis of all three phases of solar neutrino data from the Sudbury Neutrino Observatory. Phys. Rev. C 88, 025501 (2013)
6. K. Abe et al., Hyper-Kamiokande Design Report 5 (2018). arXiv:1805.04163 [physics.ins-det]
7. M. Wurm et al., The next-generation liquid-scintillator neutrino observatory LENA. Astropart. Phys. 35, 685 (2012)
8. M. Askins et al., THEIA: an advanced optical neutrino detector. Eur. Phys. J. C 80(5), 416 (2020)
9. J.F. Beacom et al., Physics prospects of the Jinping neutrino experiment. Chin. Phys. C 41(2), 023002 (2017)
10. P.C. de Holanda, A.Y. Smirnov, Homestake result, sterile neutrinos and low-energy solar neutrino experiments. Phys. Rev. D 69, 113002 (2004)
11. P.C. de Holanda, A.Y. Smirnov, Solar neutrino spectrum, sterile neutrinos and additional radiation in the Universe. Phys. Rev. D 83, 113011 (2011)
12. A. Friedland, C. Lunardini, C. Pena-Garay, Solar neutrinos as probes of neutrino matter interactions. Phys. Lett. B 594, 347 (2004)
13. I. Lopes, The Sun: light dark matter and sterile neutrinos. Astrophys. J. 905(1), 22 (2020)
14. G.T. Zatsepin, A.Yu. Smirnov, Neutrino decay in gauge theories. Yad. Fiz. 28, 1569–1579 (1978)
15. B.T. Cleveland, T. Daily, R. Davis Jr., J.R. Distel, K. Lande, C.K. Lee, P.S. Wildenhain, J. Ullman, Measurement of the solar electron neutrino flux with the Homestake chlorine detector. Astrophys. J. 496, 505 (1998)
16. W. Hampel et al., GALEX solar neutrino observations: results for GALEX IV. Phys. Lett. B 447, 127 (1999)
17. M. Altmann et al., Complete results for five years of GNO solar neutrino observations. Phys. Lett. B 616, 174 (2005)
18. J.N. Abdurashitov et al., Measurement of the solar neutrino capture rate with gallium metal. III: results for the 2002–2007 data-taking period. Phys. Rev. C 80, 015807 (2009)
19. R. Acciarri et al., Long-Baseline Neutrino Facility (LBNF) and Deep Underground Neutrino Experiment (DUNE); Conceptual Design Report. Vol. 2: The Physics Program for DUNE at LBNF, 12 (2015). arXiv:1512.06148 [physics.ins-det]
20. C.E. Aalseth et al., DarkSide-20k: a 20 tonne two-phase LAr TPC for direct dark matter detection at LNGS. Eur. Phys. J. Plus 133, 131 (2018)
21. T. Kovacs et al., Borex: solar neutrino experiment via weak neutral and charged currents in boron-11. Solar Phys. 128(1), 61 (1990)
22. L. Pfeiffer, A.P. Mills, R.S. Raghavan, E.A. Chandross, Indium-loaded liquid scintillator for low-energy solar-neutrino spectroscopy. Phys. Rev. Lett. 41, 63 (1978)
23. K. Zuber, Spectroscopy of low energy solar neutrinos using CdTe detectors. Phys. Lett. B 571, 148 (2003)
24. Z. Wang, X. Benda, S. Chen, Delayed coincidence in electron-neutrino capture on gallium for neutrino spectroscopy. Astropart. Phys. 126, 102519 (2021)
25. S. Haselschwarz, B. Lenardo, P. Pirinen, J. Suhonen, Solar neutrino detection in liquid xenon detectors via charged-current scattering to excited states. Phys. Rev. D 102(7), 072009 (2020)
26. Y. Fujita, K. Zuber, H. Fujita, Constraining the solar neutrino survival probability curve by using Li6, Li7, C12, O18, F19, and Ca42 nuclear targets. Phys. Rev. D 104(1), 013004 (2021)
27. J.N. Bahcall, Neutrino spectroscopy of the solar interior. Phys. Lett. 13, 332 (1964)
28. F. Reines, R.M. Woods, New approach to the detection of solar neutrinos via inverse beta decay. Phys. Rev. Lett. 14, 20 (1965)
29. V.A. Kuzmin, G.T. Zatsepin, On the neutrino spectroscopy of the Sun. In: Proceedings of the 9th International Cosmic Ray Conference, Vol. 1, p. 1023 (1965)
30. J.N. Bahcall, What next with solar neutrinos? Phys. Rev. Lett. 23, 251 (1969)
31. L.S. Peak, The last neutrinos of the Sun. Aust. J. Phys. 33, 821 (1980)
32. J.K. Rowley, The 7Li – 7Be Experiment. In: Proceedings Informal Conference on Status and Future of Solar Neutrino Research, NY (1978)
33. A.V. Kopylov, I.V. Orekhov, V.V. Petukhov, A.E. Solomatin, A lithium-beryllium method for the detection of solar neutrinos (2009). arXiv:0910.3889 [nucl-ex]
34. W.C. Haxton, Salty water Cherenkov detectors for solar neutrinos. Phys. Rev. Lett. 76, 1562 (1996) [Erratum: Phys. Rev. Lett. 77, 1662 (1996)]
35. J.R. Alonso et al., Advanced Scintillator Detector Concept (ASDC): a concept paper on the physics potential of water-based liquid scintillator, 9 (2014). arXiv:1409.5864 [physics.ins-det]
36. Y. Liang et al., Optical property measurements of lithium chloride aqueous solution for neutrino detection (2022). arXiv:2211.05023 [physics.ins-det]
37. Y. Fujita, Neutri as neutrino detectors. In: Proceedings of 5th International Solar Neutrino Conference, Dresden (2019)
38. J.N. Bahcall, Neutrino Astrophysics (Cambridge University Press, Cambridge, 1989)
39. Y. Shimbara et al., High-resolution study of Gamow–Teller transitions with the 35Cl(3He, t)37Ar reaction. Phys. Rev. C 86, 024312 (2012) [Erratum: Phys. Rev. C 88, 059901 (2013)]
40. K.S. Hirata et al., Observation of B–8 solar neutrinos in the Kamiokande-II Detector. Phys. Rev. Lett. 63, 16 (1989)
41. J.N. Bahcall, Neutrino-electron scattering and solar neutrino experiments. Rev. Mod. Phys. 59, 505 (1987)
42. J. Hosaka et al., Solar neutrino measurements in super-Kamiokande-II. Phys. Rev. D 73, 112001 (2006)
43. KamLAND-Zen and SNO+, Presentation at the Neutrino 2020 conference
44. J.N. Bahcall, Solar neutrino experiments. Rev. Mod. Phys. 80, 881 (1978)
45. J.N. Bahcall, Phase-space integrals for beta decay and nuclear matrix elements. Nucl. Phys. 75, 10 (1966)
46. V. Barinov, B. Cleveland, V. Gavrin, D. Gorbunov, T. Ibrigimova, Revised neutrino-gallium cross section and prospects of BEST in resolving the Gallium anomaly. Phys. Rev. D 97(7), 073001 (2018)
47. J.N. Bahcall et al., Standard neutrino spectrum from B–8 decay. Phys. Rev. C 54, 411 (1996)
48. W. Hampel et al., Final results of the 51Cr neutrino source experiments in gallex. Phys. Lett. B 420(1), 114 (1998)
49. J.N. Abdurashitov et al., Measurement of the response of a gallium metal solar neutrino experiment to neutrinos from a 51Cr source. Phys. Rev. C 59, 2246–2263 (1999)
50. J. Ashenfelter et al., The PROSPECT reactor antineutrino experiment. Nucl. Instrum. Meth. A 922, 287 (2019)
51. F.P. An et al., Independent measurement of the neutrino mixing angle θ13 via neutron capture on hydrogen at Daya Bay. Phys. Rev. D 90(7), 071101 (2014)
52. From Chemister database as of Aug. 20, (2020). Version available at http://www.chemister.ru/Database/search-en.php
53. From ENSDF database as of Nov. 18 (2019). Version available at http://www.nndc.bnl.gov/ensarchivals/
54. Z. Guo et al., Slow liquid scintillator candidates for MeV-scale neutrino experiments. Astropart. Phys. 109, 33 (2019)
55. X. Dai, E. Rollin, A. Bellerive, C. Hargrove, D. Sinclair, C. Mifflin, F. Zhang, Wavelength shifters for water Cherenkov detectors. Nucl. Instrum. Meth. A 589, 290–295 (2008)
56. W. Luo et al., Reconstruction algorithm for a novel Cherenkov scintillation detector. JINST 18(02), P02004 (2023)
57. S.D. Biller, E.J. Leming, J.L. Paton, Slow fluors for effective separation of Cherenkov light in liquid scintillators. Nucl. Instrum. Meth. A 972, 164106 (2020)
58. B.J. Land et al., MeV-scale performance of water-based and pure liquid scintillator detectors. Phys. Rev. D 103(5), 052004 (2021)
59. From John Bahcall’s webpage. http://www.sns.ias.edu/~jnb/SNdata/sndata.html
60. D. Adey et al., Measurement of the electron antineutrino oscillation with 1958 days of operation at Daya Bay. Phys. Rev. Lett. 121(24), 241805 (2018)
61. P.A. Zyla et al., Review of particle physics. PTEP 2020(8), 083C01 (2020)
62. H. Long, Phenomenological studies of Active-Sterile Neutrino Oscillations. Doctor thesis, University of Science and Technology of China (2008)
63. G. Tesic, Extraction of active and sterile neutrino mixing parameters with the Sudbury Neutrino Observatory. Doctor thesis, Carleton University (2008)
64. C. Giunti, C.W. Kim, M. Monteno, Atmospheric neutrino oscillations with three neutrinos and a mass hierarchy. Nucl. Phys. B 521, 3 (1998)
65. E.K. Akhmedov, M.A. Tortola, J.W.F. Valle, A simple analytic three flavor description of the day night effect in the solar neutrino flux. JHEP 05, 057 (2004)
66. T. Roger et al., Precise determination of the unperturbed B-8 neutrino spectrum. Phys. Rev. Lett. 108, 162502 (2012)
67. A.M. Serenelli, W.C. Haxton, C. Pena-Garay, Solar models with accretion. I. Application to the solar abundance problem. Astrophys. J. 743, 24 (2011)
68. G.J. Feldman, R.D. Cousins, A unified approach to the classical statistical analysis of small signals. Phys. Rev. D 57, 3873 (1998)
69. M. Agostini, B. Neumair, Statistical methods applied to the search of sterile neutrinos. Eur. Phys. J. C 80(8), 750 (2020)