A First Search for Solar $^8B$ Neutrino in the PandaX-4T Experiment using Neutrino-Nucleus Coherent Scattering

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A search for interactions from solar $^8B$ neutrinos elastically scattering off xenon nuclei using PandaX-4T commissioning data is reported. The energy threshold of this search is further lowered compared with the previous search for dark matter, with various techniques utilized to suppress the background that emerges from data with the lowered threshold. A blind analysis is performed on the data with an effective exposure of 0.48 ton-year, and no significant excess of events is observed. Among results obtained using the neutrino-nucleus coherent scattering, our results give the best constraint on the solar $^8B$ neutrino flux. We further provide a more stringent limit on the cross section between dark matter and nucleon in the mass range from 3 to 9 GeV/c².

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Due to complex fusion processes inside the Sun, neutrinos are continuously generated in large amount. As liquid xenon (LXe) detectors dedicated to dark matter (DM) direct search [1,3] have been developed into the multi-tonne scale in recent years, they are now able to reach the sensitivity to detect solar neutrinos via coherent elastic nuclear scattering (CEνNS). Among all sources of solar neutrinos, neutrinos produced in the β decay of $^{8}$B are the most likely ones to be detected due to the 15 MeV Q value. The flux of $^{8}$B solar neutrons on Earth has been measured to be approximately $5 \times 10^{9}$ cm$^{-2}$s$^{-1}$ [3,5], and its CEνNS has an energy spectrum hardly distinguishable from that of a 6 GeV/c$^2$ DM particle in LXe. No experimental determination of the solar neutrino flux using its CEνNS signal has been made yet. Recently, the XENON1T collaboration has published a search for the $^{8}$B CEνNS signal using 0.6 tonne-year data with no excess found [6]. Due to the low nuclear recoil (NR) energy from the $^{8}$B CEνNS, it is crucial to lower the energy threshold. In this letter, we report a search for CEνNS induced by the solar $^{8}$B neutrinos using the commissioning data of PandaX-4T (Run0) based on a blind analysis, with a dedicated data selection, which lowered the energy threshold (defined as the energy having signal acceptance of 1%) from 1.33 to 0.95 keV.

PandaX-4T dark matter direct search experiment is located in China Jinping underground Laboratory (CJPL) [7,8]. the PandaX-4T experiment utilizes a dual-phase xenon time projection chamber (TPC) with a sensitive volume of 3.7 tonne of LXe, and two arrays of photo-multipliers (PMTs) on the top and bottom of the TPC, consisting of 169 and 199 Hamamatsu 3-inch R11410-23 PMTs, respectively. Both the primary scintillation ($S_1$) and the delayed proportional scintillation from drifted electrons ($S_2$) of an event are collected by the PMTs, allowing 3-D position reconstruction with a resolution of about a few millimeter for $S_2$s of $\sim$100 photoelectron (PE) on the longitudinal and transverse directions, based on the time difference between the $S_1$ and $S_2$, and the PMT pattern of the $S_2$, respectively. The waveforms of the PMTs are digitized by CAEN V1725 digitizers and read out under the self-trigger mode when the pulse amplitude is approximately 1/3 PE above the baseline [9]. More details of the detector apparatus can be found in Refs. [9,11]. PandaX-4T has reported the most stringent constraint on the spin-independent cross sections between the nucleon and DM with the DM mass from 5 GeV/c$^2$ to 10 TeV/c$^2$ [10] using the 0.63-tonne-year data from Run0.

Compared with the search reported in Ref. [10], new data selections are developed to enhance the detection efficiency and to minimize the extra background that emerged from data. Thresholds of the $S_1$ and $S_2$ are lowered to 0.3 PE and 65 PE (both in charge), respectively, as compared with the 2 PE and 80 PE in Ref. [10]. The systematics of the background and the energy reconstruction at such low threshold form the core of this analysis. With these thresholds, two sets of data used in Ref. [10] with a total live time of about 7.5 days show a higher noise rate, likely due to micro-discharging in the TPC, and are removed from this analysis. The data selection cuts used in this analysis are described as follows. We adopt four selection cuts from the previous analysis [10], the diffusion cut ($S_2$ widths compatible with the expected fluctuation on the electron arrival time), the veto PMT cut (no signal in the PMTs outside the field cage), the fiducial volume cut (FV, 2.67 tonnes), and the single scatter cut (only one $S_2$ above 50 PE in the 1-ms event window). Events with large signals are observed to be followed by small afterglow signals in PandaX-4T and other experiments [12,13]. These afterglow signals usually are single electrons (SEs) which have a strong correlation with the previous $S_2$ in both time and position. Compared with Ref. [10], a more stringent afterglow veto based on the time and position difference to the previous event is implemented. Events with a time difference to previous $S_2$ (>2000 PE) less than 50 ms or position difference smaller than 100 mm are excluded. In addition, we veto the event unless the total charge per unit time and the number of $S_1$s in the preceding 1-ms window have returned back to normal. The afterglow veto cut also includes a set of “activity” requirements on an event waveform, that the ratio between the main $S_2$ charge and the total event charge $F_{S_2}=q_{S_2}/q_{\text{event}} > 5/6-150/q_{\text{event}}$, the integrated charge in the preceding event window to be less than 20 PE, and the main $S_1$ to be the only signal within 4-μs around it. The effective live time of this analysis is estimated to be 64.7 days.

The signal expectation in this analysis is produced by a two-step simulation. The first step is the same as in Ref. [10], in which the correlated distribution in $S_1$ and $S_2$ are produced according to a fit to the calibration data, later referred to as the signal model. In the second step, a dedicated waveform simulation (WS) is developed. The waveform of the $S_1$ is assembled using sampled $S_1$ hits from the neutron calibration data, similar to the procedure in Ref. [14]. The waveform of the $S_2$ at any given position is assembled using individual SE waveforms from the data, with the reconstructed position within a 40-mm radius circle. The width of the overall assembled waveform at a given depth in the TPC is required to satisfy the diffusion relation observed from the data. Effects of PMT afterpulsing, delayed electrons [15,16,17], and photo-ionization of impurities after a large $S_2$ are implemented in the WS according to the data. More details can be found in the appendix.

The total efficiency to the $^{8}$B CEνNS consists of four components (see Fig. 1): 1) the signal reconstruction, 2) the data selections discussed two paragraphs earlier, 3) the region-of-interest (ROI), and 4) a cut based on boosted decision tree (BDT, see later text). The signal reconstruction includes clustering of PMT hits into signal pulses, classification of the signal pulses into $S_1$s and $S_2$s, and pairing of the classified $S_1$s and $S_2$s into incident events. Each step of the signal reconstruction is affected
by the presence of dark noises and stray electrons. For the ROI, we require the number of coincident PMT hits in an $S1$ to be either 2 or 3 in this analysis. The events with only a single-hit $S1$ are mostly accidental background originating from the PMT dark noises, and are excluded from the ROI due to a poor signal-to-background ratio. The $S2$ charge range, uncorrected for spatial dependence, is further optimized to be 65–230 PE for 2-hit $S1$ and 65–190 PE for 3-hit $S1$ based on the expected signal-to-background ratio. This ROI requirement has dominating effects on the signal efficiency. The efficiencies of 1), 2) and 3) are estimated using the WS and validated by the neutron calibration data, with their fractional difference (14%) taken as the systematic uncertainty.

We take the calculated deposit energy spectrum of the solar $^8$B CE$
u$NS in LXe from Ref. [18], which is shown in Fig. 1. The signal model implements the light and charge production in LXe following the NEST v2.3.6 parametrization [19], and the response of signal detection in the PandaX-4T detector, similar to Ref. [10]. The light and charge yields are extrapolated from the one used in Ref. [10], which has its model parameters fit to the neutron calibration data in the energy region of the DM search (see Fig. 2). We adopt the relative uncertainties of the light and charge yields from NEST [20], which is based on a global fit to all available measurements, and conservatively assume them to be uncorrelated.

The background composition is the same as Ref. [10]. With loosened $S1$ and $S2$ selections, the accidental coincidence (AC) background increases significantly in comparison to Ref. [10], which dominates the overall background. The electronic recoil (ER), NR, and surface background are estimated using the same method as in Ref. [10] but with the new data selections and the ROI cut.

The rate of the AC background is estimated using random $S1$s and $S2$s identified in the data. The $S2$s are first selected from a waveform (~1000 per day within 65 to 300 PE), then we search backward for 1.5 ms for a main $S1$. The 1.5-ms window is chosen so that the corresponding “activity” cuts are sufficiently similar to those mentioned earlier. The AC pair is formed when the time difference between the $S1$ and $S2$ is within [0.9, 1.5] ms, beyond the TPC’s maximum drift time (off-window), to guarantee that there is no correlation. To enlarge the statistics of the AC samples, a “scrambled” waveform data set is constructed. The waveform of the selected $S2$ is concatenated after a 1-ms segment randomly selected from our recorded data, which on average contains 6.3 (0.01) of the $S1$-like signals with the $S1$ hit equals to (larger than) 1, primarily from dark noises. This “scrambled” data get passed to the aforementioned software reconstruction and data selection. The predicted number of AC events in the ROI in the 2- and 3-hit regions can be found in Table I. The diffusion cut is the most effective cut, which suppresses the AC by a factor of 8 or so. The AC model is validated using the events with the $S2$ in the range from 300 to 800 PE (referred to as the sideband data) and within the FV, which is dominated by the AC (see Table I). The comparison between the sideband data and the prediction is given in Table I.
FIG. 3. The $S_1$ (left panels) and $S_2$ (right panels) spectra in the side-band (top panels) and ROI (bottom panels) for the 2-hit data, with the data and corresponding predictions overlaid. The shaded regions represent the 1σ uncertainty of the prediction (30%). We also overlay the expected $^8$B CEνNS spectra (scaled up by 50) in the bottom panels, shown in blue solid lines. The goodness-of-fit p-values of the $S_1$ and $S_2$ spectra in the side-band and ROI are all no less than 0.1.

TABLE I. ROI comparison: prediction vs. observation in the optimized $S_2$ ranges. Number of the pre- and post-BDT events are listed in separate rows. The observed events after unblinding are shown in the last column.

| $N_{hit}$ | $S_2$ range [PE] | BDT | ER | NR | Surf | AC | Total | BKG | $^8$B | Obs |
|-----------|-----------------|-----|----|----|------|----|-------|-----|------|-----|
| 2         | 65-230          | pre | 0.04 | 0.10 | 0.14 | 62.43 | 62.71 | 2.32 | 59   |
|           |                 | post| 0.02 | 0.04 | 0.03 | 1.41 | 1.50 | 1.42 | 1    |
| 3         | 65-190          | pre | 0.01 | 0.05 | 0.08 | 0.79 | 0.93 | 0.42 | 2    |
|           |                 | post| 0.00 | 0.02 | 0.03 | 0.02 | 0.07 | 0.29 | 0    |

TABLE II. Side-band comparison: prediction vs. observation for $S_2$ within [300, 800] PE.

| $N_{hit}$ | Physical | AC | Total | Obs |
|-----------|----------|----|-------|-----|
| 1         | 9.4      | 2060.5 | 2069.9 | 2043 |
| 2         | 10.1     | 33.8 | 43.9 | 47  |
| 3         | 6.9      | 2.2 | 9.1 | 7   |

A BDT algorithm [25] is trained to optimize the $^8$B CEνNS selection against the AC background. The $S_2$s of the AC events are mostly generated out of the fiducial region (such as the surface of electrodes and the gas region), and the $S_1$s are mostly dark noises (see Ref. [26]), both having different characters from the physical events. The input variables of the BDT concern features related to the charge, width, top-bottom asymmetry, and PMT top patterns of the $S_1$ and $S_2$ signals. The training and testing samples of the $^8$B signal in the BDT are from the WS with the $(S_1, S_2)$ distribution following our $^8$B signal model. The BDT cut value and the $S_2$ range for each $S_1$ hit bin are determined by maximizing the probability of discovering a $^8$B signal under our background model, with results summarized in Table I. The optimized BDT efficiency of the $^8$B signal is shown in Fig. 1. The BDT reduces the $^8$B CEνNS signal (AC background) by about 39% (98%) and 31% (96%), respectively, for the 2- and 3-hit bins. Most of the rejection power against the AC is gained through the parameters related to the $S_2$ waveform shape and its top charge pattern, and we observe almost no correlation in the $S_1$ and $S_2$ discriminants. The uncertainties of the BDT efficiency to the $^8$B CEνNS and the DM signals are studied using the neutron calibration data. To improve the statistics in the ROI, especially for $S_2$ less than 100 PE, the minor $S_2$s of the neutron double-scatter events are used. A difference of 14% and 13% are observed for the 2-hit and 3-hit ROI, respectively, taken as the systematic uncertainties. The systematic uncertainty of the BDT efficiency to the AC background is estimated by checking the performance on an alternative AC model using a more traditional approach based on the random pairing of the isolated $S_1$s and $S_2$s [26], leading to an uncertainty of 19% and 18% in the 2-hit and 3-hit bins.
The data within the ROI were blinded before we finalized the data selection, the background and signal models, the ROI, and the BDT optimization. We then unblinded the data and checked the events before and after applying the BDT. We show the comparison of the S1 and S2 spectra between the prediction and data before applying the BDT in Fig. 3. The observed number of the events in the ROI for the 2- and 3-hit regions are given in Table I. After unblinding, 1 (with S1=1.6 PE and S2=165 PE) and 0 events that survive the BDT are found in the 2- and 3-hit ROI, respectively.

We perform a single statistical interpretation based on 2-bin profile likelihood ratio (PLR) analysis [31] using the 2- and 3-hit data. The binned likelihood is defined as [32]:

\[ L = G(\delta_\nu)G(\delta_s)G(\delta_\theta) \]
\[ \times \prod_i G(\delta^{\text{BDT},s}_i)G(\delta^{\text{BDT},b}_i)\frac{\lambda_i N_i}{N_i!} e^{-\lambda_i}, \]  

where the index \(i\) represents the hit number of \(S1\) (2 or 3), and \(\delta (\delta^b)\) is series of the constrained nuisance parameters, which are correlated (independent) between the 2- and 3-hit bins with a Gaussian penalty \(G\) with the mean at zero. The set of parameters include \(\delta_\nu, \delta_s, \delta_\theta, \delta^{\text{BDT},s}_i, \delta^{\text{BDT},b}_i\), and \(\delta_\Phi\), corresponding to the relative uncertainties of the pre-BDT efficiency (including the signal reconstruction, data selection, and ROI), the NR signal rate, the AC background rate, the BDT cut efficiency to the NR signals, the BDT efficiency to the AC background, and the \(8B\) neutrino flux, respectively. The 1\(\sigma\) values of the nuisance parameters are summarized in Table III. The parameter \(\delta_s\) is factored together with the fractional uncertainty of the signal rate \(f_s\) which depends on the signal spectrum (\(f_s^0\) for the \(8B\) CE\(e\)NS signal and \(f^x_f\) for the DM signal), in order to reflect the common origin of \(f_s\). Typical numbers of \(f_s\) are 0.45 (0.60), 0.29 (0.39), and 0.16 (0.24) for 4-GeV\(/c^2\) DM, the \(8B\) CE\(e\)NS, and 8-GeV\(/c^2\) DM in the 2-hit (3-hit) region. \(\lambda_i\) is the expected count while \(N_i\) is the observed count. Specifically, under the hypotheses of a) the solar \(8B\) neutrino CE\(e\)NS without the DM, and b) the low mass DM with the \(8B\) CE\(e\)NS background, the expected counts can be written as:

\[ \lambda_i^\nu = N_\nu(1 + \delta_\nu f^\nu_s)(1 + \delta_\lambda)(1 + \delta^{\text{BDT},s}_\nu) + N_{\text{AC}}(1 + \delta_\lambda)(1 + \delta_\Phi)(1 + \delta^{\text{BDT},b}_\nu) + N_{\text{other}} \]
\[ \lambda_i^\chi = N_\chi(1 + \delta_\chi f^\chi_s)(1 + \delta_\lambda)(1 + \delta^{\text{BDT},s}_\chi) + N_{\text{AC}}(1 + \delta_\lambda)(1 + \delta_\Phi)(1 + \delta^{\text{BDT},b}_\chi) + N_{\text{other}} \]  

where \(N_\nu, N_{\text{AC}}, N_{\text{other}}\), and \(N_\chi\) are the nominal numbers of counts for the \(8B\) CE\(e\)NS, AC, other background events (including ER and neutron), and low mass DM, respectively. The total backgrounds predicted in the 2- and 3-hit ROI for the solar \(8B\) neutrino search are 1.50 and 0.07, respectively, in an exposure of 0.48 ton\(e\) year, as shown in Table I. The observed number of events is consistent with both background-only hypotheses in searching for the \(8B\) CE\(e\)NS and the low mass DM in Eqn. 2, representing a probability of 53\% and 17\% of observing the same or less number of events than the data, respectively.
Using a similar procedure as in Refs. [10] 31, we give the 90% C.L. upper limit on the solar $^8$B neutrino flux using the CEνNS channel, pushing the upper limit to 9.0×10^6/cm^2/s, in comparison to (5.46±0.66)×10^6/cm^2/s from the standard solar model B16-GS98 [27]. If the signal model adopted by XENON1T [6] is used, the upper limit of the solar $^8$B neutrino flux will be lowered by 13%. If the signal model uncertainty ($\delta_5$) is eliminated from the fit, the upper limit will be reduced by 10%. Under the nominal $^8$B CEνNS rate, we also obtain the best constraints on the spin-independent DM-nucleon cross section with mass in the range of 3 to 9 GeV/c^2. The results are summarized in Fig. 4. In Fig. 4, we also show the $^8$B neutrino floor curves from Ref. [18] under ideal background assumption. The current stage of PandaX has clearly entered into the sensitive region for neutrinos, so this result could also be cast into interesting parameter space of neutrino interactions. The lack of CEνNS excess from this work and XENON1T [6] also motivates further investigations on the response of LXe TPC to ultralow energy nuclear recoils.

In summary, a search for CEνNS from the solar $^8$B neutrinos as well as the low mass DM-nucleon interactions is performed using the PandaX-4T commissioning data with 0.48 tonne-year exposure. In the analysis, we have further optimized the data selection and developed various techniques to lower the energy threshold and to control the accidental background. No significant excess is observed, leading to the strongest upper limit on the solar $^8$B neutrino flux using CEνNS, and on the spin-independent DM-nucleon cross section within the mass range from 3 to 9 GeV/c^2. This manifests the potential of PandaX-4T as a highly sensitive multi-purpose dark matter and astrophysical neutrino observatory.

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Appendix on waveform simulation. To have sufficient high-purity samples for estimating the efficiency in the ROI and for training the boosted decision tree (BDT) algorithm, a waveform simulation (WS) is developed, which includes our best knowledge from the data. The WS not only simulates the S1 and S2 pulses, but also simulates the accompanying noises that could appear in the event waveform, such as the PMT afterpulsing, the delayed electrons, the photo-ionization, and the spurious S1s [13] 15] 17.

The simulation of the S1 and S2 pulse waveforms is driven. The simulated S1 pulse waveform is sampled using the real S1 hits from the neutron calibration data with the charge from 20 to 80 PE. The width distribution of the simulated S1s and S1s from the neutron calibration data in the ROI can be found in the top panel of Fig. 5. The simulated S2 pulse waveform is re-assembled using the single electron (SE) waveforms obtained from the data. The SEs are sampled within a circle with a radius $R_0=40\text{ mm}$ based on their reconstructed positions. $R_0$ is tuned to match the root-mean-square distance of all fired top PMTs, weighted by charge, from the position of the top PMT that sees the most S2 charge ($\sigma_{pos}$). With $R_0=40\text{ mm}$, the comparison of $\sigma_{pos}$ between the neutron calibration data and WS are shown in the middle panel of Fig. 5. The pileup of the SEs is required to follow
a Gaussian distribution with the Gaussian $\sigma$ equals to $\sqrt{2DT}$, where $D$ is the longitudinal diffusion coefficient in LXe and $T$ is the drift time of the simulated $S2$. The value of $D$ is obtained to be $28\, \text{cm}^2/\text{s}$ by matching the $S2$ width vs. drift time distribution of the neutron calibration data. The comparison of the $S2$ width distribution between the neutron calibration data and WS in the ROI can be found in the bottom panel of Fig. 5.

Dark counts and noises are included by inserting randomly picked 1-ms-long waveforms from all the recorded waveforms into the simulated event window. PMT afterpulsing are already included, since the simulated $S1$ and $S2$ are both sampled using the waveforms from the data. Delayed electrons and impurity photo-ionization can cause small delayed $S2$ signals after a large $S2$. The time profile and probability of such delayed $S2$s are obtained by analyzing the data waveforms after the main $S2$. The parameter which is mostly sensitive to the noise and afterglows is the $F_{S2}$ that is defined in the main text. Fig. 6 shows the comparison between the $F_{S2}$ distributions from the neutron calibration data and the WS.

FIG. 6. Comparison between the $F_{S2}$ distributions from the WS (red solid line) and data (black dots with error bars).

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