Search for Coherent Elastic Scattering of Solar \(^8\)B Neutrinos in the XENON1T Dark Matter Experiment

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Editors’ Suggestion

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We report on a search for nuclear recoil signals from solar $^8$B neutrinos elastically scattering off xenon nuclei in XENON1T data, lowering the energy threshold from 2.6 to 1.6 keV. We develop a variety of novel techniques to limit the resulting increase in backgrounds near the threshold. No significant $^8$B neutrinoelike excess is found in an exposure of 0.6 t × y. For the first time, we use the nondetection of solar neutrinos to constrain the light yield from 1–2 keV nuclear recoils in liquid xenon, as well as nonstandard neutrino-quark interactions. Finally, we improve upon world-leading constraints on dark matter-nucleus interactions for dark matter masses between 3 and 11 GeV c$^{-2}$ by as much as an order of magnitude.

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Introduction.—Neutrinos from the Sun, atmospheric cosmic-ray showers, and supernovae can produce observable nuclear recoils (NRs) via coherent elastic scattering off nuclei in liquid xenon (LXe) detectors searching for dark matter (DM) [1]. The coherent elastic neutrino-nucleus scattering (CEνNS) process [2–5] produces the same signature as the one expected from DM-nucleus interactions, and thus the two can only be distinguished by their recoil spectra. Solar $^8$B neutrinos are expected to contribute the greatest number of CEνNS events in LXe DM search experiments. These events fall near the energy thresholds of such detectors, with a spectrum indistinguishable from 6 GeV c$^{-2}$ DM.

The XENON1T dark matter search experiment, operated at the INFN Laboratori Nazionali del Gran Sasso (LNGS) until December 2018, used a sensitive target of 2.0 t of LXe in a two-phase time projection chamber (TPC). Two arrays of photomultiplier tubes (PMTs) at the top and bottom of the TPC allowed simultaneous detection of scintillation light (S1) and, via electroluminescence, ionization electrons (S2) [6,7]. With the largest exposure of any LXe TPC, data from XENON1T has been used to search for a variety of DM candidates, resulting in world-leading upper limits for DM-nucleus interactions [8–11]. Though no excess of CEνNS from $^8$B neutrinos ($^8$B CEνNS) was observed due to the energy threshold in these analyses, they will soon become an important background given the large exposures of next-generation multi-ton LXe detectors [12–14]. In this Letter, we present a search for $^8$B CEνNS events in XENON1T data between February 2, 2017 and February 8, 2018 (“SR1” in Ref. [8]). In this new analysis, we achieve unprecedented sensitivity by reducing the energy threshold.

Analysis strategy.—The $^8$B CEνNS expectation in XENON1T depends on the $^8$B neutrino flux $\Phi$, measured [15,16]] as $(5.25 \pm 0.20) \times 10^6$ cm$^{-2}$ s$^{-1}$; the CEνNS cross section, from the standard model; the nuclear recoil scintillation light yield in xenon $L_y$; and the ionization yield $Q_y$. We first present a search for $^8$B CEνNS events in XENON1T, expecting 2.1 CEνNS events given nominal estimates of the above variables. We then combine XENON1T data with external measurements, as appropriate, to constrain these variables. We constrain $L_y$ by considering external measurements of $Q_y$ and $\Phi$. Next, by including external measurements of $Q_y$ and $L_y$, we use XENON1T data to determine $\Phi$ independently. We also constrain nonstandard neutrino interactions by relaxing the standard model assumption on the CEνNS cross section. Finally, by considering $^8$B CEνNS as a background and applying external constraints on all variables, we use the data to set limits on DM-nucleus interactions.

CEνNS signal.—The expected recoil spectrum of $^8$B CEνNS in LXe is shown in Fig. 1 (top, dotted red). The scintillation and ionization responses are relatively uncertain at $^8$B CEνNS energies (<2 keV), and NR calibration measurements in XENON1T scarcely overlap this region, instead producing S1s and S2s similar to DM of mass ≥30 GeV c$^{-2}$. Therefore, we modify the NR model in Refs. [8,17] by decoupling the light and charge yields to allow for additional freedom.

The NR charge yield $Q_y$ has been measured down to 0.3 keV [19], providing strong constraints at $^8$B CEνNS energies which are included in v2.1.0 of the NEST package [21]. We use the best fit and uncertainty from NEST to define the shape of $Q_y$, fitting a single free “interpolation parameter” $q$ to the measurements which specifies $Q_y$ within this uncertainty, resulting in the model shown in Fig. 1 (middle). The central black line (edges of the shaded interval) in the figure corresponds to $q$ equaling 0 (±1). Measurements of the LXe NR light yield $L_y$ [20] have a large (∼20%) uncertainty near 1 keV. Since the NEST $L_y$ uncertainty is largely set by measurements at energies far above our region of interest (ROI), we fit these measurements using a free parameter that scales the NEST best-fit...
High-energy events from gamma-ray backgrounds can significantly affect the performance of dark matter detectors. To address this, a new method is introduced that focuses on the tight-coincidence requirement for events, leading to a 1% acceptance of CEνNS events. This allows for the calculation of the recoil spectrum of 8B CEνNS or dark matter of mass 6 GeV c\(^{-2}\) with a cross section of \(10^{-14}\) cm\(^2\) and an energy where 5% of recoils are detected, from 2.6 to 1.6 keV. The overall rate of isolated S1s increases by 20-fold with respect to previous NR searches [8,10,11] because of the relaxed tight-coincidence requirement and lower S2 threshold, derived from integrating the expected event rate in Fig. 1 (top). Due to the minimal overlap with previously studied data, this analysis considers all backgrounds described in Refs. [8,17]. Radon daughters decaying on the inner surface of the TPC wall produce events with reduced S2s, contributing to the background in the ROI. In order to reduce this background to a negligible level, we use a fiducial volume of 1.04 t, similar to the one chosen for Ref. [18] but smaller than the one used in Ref. [8].

The accidental coincidence (AC) of S1 and S2 peaks incorrectly paired by the XENON1T reconstruction software mimics real interactions. AC background events are modeled by sampling (with replacement) from isolated S1s and S2s and assigning a random time separation between them. Most S1s contributing to AC events originate from the pileup of lone hits from individual PMTs. Other sources include low-energy events occurring below the cathode or on the inner detector surface, and light leaking inside the active volume. AC forms the dominant background for this search, since the overall rate of isolated S1s increases by 2 orders of magnitude when we require only two hits. The rate and distribution of isolated S1s are determined using S1 peaks found in the extended event window of 1 ms before the S1 of high-energy events, as in Refs. [8,17]. For this analysis, the data is reprocessed with an updated algorithm [29] to better retain the isolated S1s preceding these high-energy events, eliminating the dominant systematic uncertainty in the AC rate [8].

High-energy events from gamma-ray backgrounds can also contaminate subsequent events with lone hits, a

\[ L_{\nu} \] These measurement and the resulting model are shown in Fig. 1 (bottom). The \( L_{\nu} \) and \( Q_{\nu} \) parameter fits use external measurements between 0.9 and 1.9 keV, a central interval containing 68% of expected 8B CEνNS events after all acceptance losses. We conservatively assume zero \( L_{\nu} \) below 0.5 keV, the lowest energy measurement available [22]. This treatment has a percent-level effect on the expected CEνNS rate, since the detection efficiency below this “cutoff energy” is \(<10^{-3}\).

The XENON1T S1 detection threshold was previously limited by the requirement that three or more PMTs detect pulses above threshold (denoted as “hits”) within 50 ns [23], leading to a 1% acceptance of CEνNS recoils above the 0.5 keV cutoff. We reduce this “tight-coincidence” requirement to two hits within 50 ns, increasing the total acceptance above the 0.5 keV cutoff to 5%. Another efficiency loss comes from 8B CEνNS S2s failing the software trigger, which requires 60 significant PMT signals [24], or the S2 analysis threshold. The sensitivity is therefore impaired by the presence of electronegative impurities in the LXe, which reduce S2s along the drift path. The 120 PE S2 acceptance threshold, reduced from 200 PE, accepts 92% of CEνNS events that pass the software trigger. Acceptance losses due to new event selection criteria introduced to suppress backgrounds are described below. Figure 1 (top) shows the S1 tight-coincidence acceptances, software trigger, and S2 threshold acceptances, and total acceptances for this and previous analyses, and the resulting spectra of expected 8B CEνNS events. The Supplemental Material of this Letter provides details on the waveform simulation used to calculate all acceptances, and demonstrates excellent matching between real and simulated S1s and S2s [25]. The overall change in acceptance results in a lowering of the energy threshold, defined as the energy where 5% of recoils are detected, from 2.6 to 1.6 keV. The ROI for the CEνNS search is defined by S2s between 120 and 500 photoelectrons (PE), and S1s between 1.0 and 6.0 PE consisting of two or three hits.

In this ROI, the 8B CEνNS signal expectation increases 20-fold with respect to previous NR searches [8,10,11] because of the relaxed tight-coincidence requirement and lower S2 threshold, derived from integrating the expected event rate in Fig. 1 (top). Because of the minimal overlap with previously studied data, we consider this a blind analysis.

**Backgrounds.**—This analysis considers all backgrounds described in Refs. [8,17]. Radon daughters decaying on the inner surface of the TPC wall produce events with reduced S2s, contributing to the background in the ROI. In order to reduce this background to a negligible level, we use a fiducial volume of 1.04 t, similar to the one chosen for Ref. [18] but smaller than the one used in Ref. [8].

The accidental coincidence (AC) of S1 and S2 peaks incorrectly paired by the XENON1T reconstruction software mimics real interactions. AC background events are modeled by sampling (with replacement) from isolated S1s and S2s and assigning a random time separation between them. Most S1s contributing to AC events originate from the pileup of lone hits from individual PMTs. Other sources include low-energy events occurring below the cathode or on the inner detector surface, and light leaking inside the active volume. AC forms the dominant background for this search, since the overall rate of isolated S1s increases by 2 orders of magnitude when we require only two hits. The rate and distribution of isolated S1s are determined using S1 peaks found in the extended event window of 1 ms before the S1 of high-energy events, as in Refs. [8,17]. For this analysis, the data is reprocessed with an updated algorithm [29] to better retain the isolated S1s preceding these high-energy events, eliminating the dominant systematic uncertainty in the AC rate [8].

High-energy events from gamma-ray backgrounds can also contaminate subsequent events with lone hits, a
dominant source of S1s in this analysis. For each event, the preceding event with the highest potential to produce lone hits is identified by dividing its largest S2 area by its time difference from the current event, denoted as $S_{2\text{prev}}/\Delta t_{\text{prev}}$. The selection $S_{2\text{prev}}/\Delta t_{\text{prev}} < 12$ PE $\mu s^{-1}$ reduces the rate of isolated S1s by 65%, accepting 87% of $^8B$ CE$_{e\gamma}$NS signals. Furthermore, we require the PMT signal sum within the first 1 ms of an event to be $<40$ PE and that this interval contains at most a single S1, accepting 96% of remaining events. After these selections, the total isolated-S1 rate is 11.2 Hz, 10 times higher than for a threefold tight-coincidence requirement [8]. The total exposure after these selection criteria is 0.6 $t \times y$.

The same high-energy events can also produce small S2s appearing in subsequent events [30], potentially leading to unaccounted-for correlations between the isolated-S1 and isolated-S2 samples. In order to reduce these correlations, we further require that no S2 signal is found within the first millisecond of the event, and apply a cut on the horizontal spatial distance between the current and previous S2. These selections, together with the selection on $S_{2\text{prev}}/\Delta t_{\text{prev}}$, allow us to model the AC background for S2s down to 80 PE and reduce the isolated-S2 event rate therein to 1.0 mHz. For comparison, the isolated-S2 event rate in Ref. [8] was 2.6 mHz for S2s above 100 PE [8].

Selections that require both S1 and S2, such as the fiducial volume and S2 signal width [23] cuts (which depend on the interaction depth Z), are next applied to the combined synthetic AC events. Interactions on the TPC electrodes and in the xenon gas above the liquid surface contribute significantly to the isolated-S2 event rate, motivating a selection in a high-dimensional feature space as in Ref. [9]. In this analysis, a gradient boosted decision tree (GBDT) [31] ensemble is trained using the scikit-learn package [32] to optimize the signal and AC background discrimination based on the S2 area, the S2 rise time, the fraction of S2 area on the top array of PMTs, and Z. The GBDT selection reduces the AC background by 70% while accepting $\geq 85\%$ of $^8B$ CE$_{e\gamma}$NS events.

A background control region with S2 $< 120$ PE contains $>50\%$ of the AC background, and is excluded from the search for $^8B$ CE$_{e\gamma}$NS due to its low detection probability. After closer inspection of the candidate waveform events in the control region, four events whose S1s contain more than one hit in the same channel, possibly due to afterpulsing of the PMTs [7], were removed. Twenty-three events remain, consistent with the AC background prediction of 27.7 $\pm$ 1.4 events in the control region. Though the methods above yield a $\leq 5\%$ uncertainty on the AC background, we conservatively use an uncertainty of 20% in the analysis to reflect the statistical uncertainty from the control region, but find that the CE$_{e\gamma}$NS search is not strongly dependent on the uncertainty value within this range. Figure 2 shows the AC model, events failing the GBDT cut, and science data projected onto Z and quantiles of $S_{2\text{prev}}/\Delta t_{\text{prev}}$.

Neutrons originating from radioimpurities inside detector materials produce NRs in the TPC, but the tight ROI reduces these to $0.039^{+0.002}_{-0.003}$ events. To limit the electronic recoil (ER) background dominated by $\beta$ decays of $^{214}$Pb (a daughter of $^{222}$Rn), we additionally require $cS2_h$, the S2 area in the bottom array after a position-dependent correction [8], to be $<250$ PE. This reduces the ER background to $0.21 \pm 0.08$ events in the ROI, leading to a 4.2% absolute acceptance loss for CE$_{e\gamma}$NS. The same simulation procedure described in Ref. [17] is used to assess the neutron and ER backgrounds, as well as the associated uncertainties. The selection on $cS2_h$ has negligible effect on the AC background.

In the interpretation of the data, we utilize several features that differ between true S1–S2 events and AC. Lone hits are spread uniformly across the top and bottom PMT arrays, whereas scintillation light from the LXe volume mostly falls on the bottom array. Furthermore, an S1 with more than 2 PE on one PMT is very unlikely to be part of an AC, since most lone hits in XENON1T consist of a single photoelectron. We split the data into six “hit categories” according to the number and arrangement of S1 hits, and the largest hit-area (LHA), listed in Table I.

**Inference.**—We analyze the data with a statistical model adapted from Ref. [17], with three continuous analysis...
TABLE I. Signal and background expectation values and observed event counts in six S1 hit classes based on number of S1 PMT hits in total, the number in the top array (TA), and the largest hit-area (LHA). Expectation values are computed for the nominal (NEST best fit) $Q_y$, $L_y$, and $^8\text{B}$ neutrino flux for the 0.6 $t \times y$ exposure. The neutron background is not shown separately in the table as it is significantly smaller than AC and ER. The neutron background was not shown separately in the table as it is significantly smaller than AC and ER. By including external constraints on $Q_y$ and $L_y$, this analysis can be used to consider physics processes beyond the standard model. We consider a benchmark model in which nonstandard neutrino interactions modify the CE$_{\nu}$NS cross section [3, 34, 35]. Our confidence interval on $\Phi$ assuming the standard model cross section can be reinterpreted as a confidence interval on the modified CE$_{\nu}$NS cross section if we use the externally measured value of $Q_y$. We also consider DM-nucleus interactions, including CE$_{\nu}$NS as a background contribution, and $Q_y$ and $L_y$ as nuisance parameters. We use the same profile construction approach to compute upper limits as Ref. [17], including a power constraint [36].

Results.—We estimated the probability of observing a $3\sigma(2\sigma)$ CE$_{\nu}$NS excess in this data to be 20% (50%) for the nominal (NEST best fit) values of $Q_y$, $L_y$. Inverting the GBDT cut gave an AC-rich validation region that was unblinded first (Table I). Background-only goodness-of-fit (GOF) tests using a binned Poisson likelihood were performed on the validation region, both for the six S1 hit categories and in the continuous analysis space, with $p$ values of 0.95 and 0.33, respectively, which exceeded the 0.05 validation criterion. The science dataset was unblinded following the successful validation region unblinding. Six events were found, as listed in Table I. The events are compatible with the background-only hypothesis, with a CE$_{\nu}$NS discovery significance of $p > 0.50$. The same GOF tests used to assess the validation region unblinding show good agreement, with $p = 0.64$ and $p = 0.72$, respectively.

To construct confidence intervals in $\Phi$, $Q_y$, and $L_y$, we define a test statistic from the sum of profiled log likelihoods of XENON1T and external constraints. By including external measurements of $Q_y$, we can constrain $L_y$. Since the CE$_{\nu}$NS signal spans a narrow energy range, we use a constant $L_y$ value to construct the intervals. This allows us to make use of the degeneracy between $\Phi$ and the NR response parameters $Q_y$ and $L_y$, all three of which primarily affect the CE$_{\nu}$NS expectation value. Details on the construction of these confidence intervals may be found in the Supplemental Material [25].

Dimensions; S2, Z, and the quantiles of equal signal acceptance in $S_{prev}/\Delta t_{prev}$. The likelihood for XENON1T is the product of the likelihoods for each hit category, indexed with $i$

$$L_{\text{Xe1T}}(\Phi, Q_y, L_y, \bar{\theta}) = \prod_{i=1}^{6} L_i(\Phi, Q_y, L_y, \bar{\theta}) \times \prod_m [L_m(\theta_m)].$$

(1)

Here, $\bar{\theta}$ are the nuisance parameters. The extended unbinned likelihood terms $L_i(\Phi, Q_y, L_y, \bar{\theta})$ are of the same form as Eq. (20) in Ref. [17], and include models in S2, Z, and $S_{prev}/\Delta t_{prev}$ for the $^8\text{B}$ CE$_{\nu}$NS signal and AC, ER, and neutron backgrounds. The background component rates $\theta_m$ are constrained by the external measurement terms $L_m(\theta_m)$.

For the $^8\text{B}$ CE$_{\nu}$NS search, the nuisance parameters are the expectation values of the backgrounds, each with a constraint term, as well as the NR response parameters $Q_y$ and $L_y$. The total likelihood used in the CE$_{\nu}$NS search is the product of $L_{\text{Xe1T}}$, defined in Eq. (1), and external constraints on $Q_y$ and $L_y$, as detailed above. For these results, the models of CE$_{\nu}$NS, DM, and the neutron background change both in shape and expectation value with $Q_y$ and $L_y$. The CE$_{\nu}$NS discovery significance as well as DM upper limits are computed using the log-likelihood-ratio test statistic calibrated with toy Monte Carlo (toy-MC) simulations [17, 33].
shown by the green shaded region in Fig. 3 (top). On the other hand, $\Phi$ can be constrained if the external constraints on $Q_y$ and $L_y$ are included, as shown in the pink region, with a 90% upper limit on $\Phi$ of $1.4 \times 10^7$ cm$^{-2}$ s$^{-1}$. The blue region in Fig. 3 shows the confidence interval from a combination of the XENON1T likelihood, constraints on $\Phi$ [16], and on $Q_y$. The 90% upper limit on $L_y$ (assumed constant over the 0.9–1.9 keV energy range) is 9.4 ph/keV.

In the benchmark model of nonstandard neutrino interactions considered, the electron neutrino has vector couplings to the up ($u$) and down ($d$) quarks of $e^\nu_{ee}$ and $e^\nu_{
u e}$, respectively [3,34,35]. The 90% confidence interval for $e^\nu_{ee}$ and $e^\nu_{
u e}$ from XENON1T data is shown in light blue in Fig. 4 (top).

The result for a spin-independent DM-nucleus interaction is shown in Fig. 4 (bottom). This constraint improves on previous world-leading limits [8,9] in the mass range between 3 and 11 GeV c$^{-2}$ by as much as an order of magnitude. The limit lies at roughly the 15th percentile, reflecting the downwards fluctuation with respect to the background model (including CE$\nu$NS), but is not extreme enough to be power constrained.

**Outlook.**—The XENONnT experiment, currently being commissioned at LNGS, aims to acquire a 20 t \( \times \) y exposure [14]. As the isolated-S1 rate scales up with the larger number of PMTs and the isolated-S2 rate with the detector surface area, the AC background will be the biggest challenge for the discovery of $^8$B CE$\nu$NS. The AC background modeling and discrimination techniques used in this analysis will improve the sensitivity of XENONnT to $^8$B CE$\nu$NS and low-mass DM. The novel cryogenic
liquid circulation system developed to ensure efficient purification in XENONnT will mitigate the reduction of S2s due to impurities, improving the acceptance of low-energy NRs from $^8$B neutrinos and DM. Additionally, the data will be analyzed in a triggerless mode to minimize efficiency loss and better understand the AC background. Together with the significantly larger exposure, these techniques give XENONnT strong potential to discover $^8$B CE$
u$NS.

The large uncertainty in both $Q_1$ and $L_y$ will be the dominant systematic in constraining new physics from DM and nonstandard neutrino interactions. Improving these uncertainties by calibrating NRs in LXe using in situ low energy neutrion sources [46] and dedicated detectors [19] can crucially improve the sensitivity of next-generation experiments to both $^8$B CE$
u$NS and light DM.

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