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


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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 neutrino-like excess is found in an exposure of 0.6 $t \times y$. 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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FIG. 1. Top: Improvement of the NR acceptance in this work (solid) with respect to previous DM analyses (dashed) [8,18], including S1 detection efficiency (blue), software trigger and S2 threshold acceptance (green), and total acceptance after other quality and background rejection cuts (black). The right axis shows the recoil spectrum of $^8$B CEνNS or dark matter of mass 6 GeV $c^{-2}$ and cross section $4 \times 10^{-45}$ cm$^{-2}$ (dotted pink), and the products of this spectrum with the total acceptances (red) as a function of true recoil energy. The acceptances and resulting spectra are based on the nominal (NEST) yield models. The red shaded interval contains 68% of expected CEνNS events. Middle: The most precise available measurements of $Q_y$ [19] (orange), with the $Q_y$ model described in the text overlaid (black). Bottom: Constraints on $L_y$ (in photons per keV) from LUX (orange) [20], and the 68% upper limit from this work described in the Results section (blue), with the $L_y$ model described in the text overlaid (black). To be conservative, no response is assumed below the 0.5 keV cutoff (hatched gray).

$L_y$. These measurement and the resulting model are shown in Fig. 1 (bottom). The $L_y$ and $Q_y$ parameter fits use external measurements between 0.9 and 1.9 keV, a central interval containing 68% of expected $^8$B CEνNS events after all acceptance losses. We conservatively assume zero $L_y$ 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 $^8$B 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 analysis 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 $^8$B 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 $^8$B 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 \(^{8}\text{Be}\) CE\(_{2}\)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 \(^{8}\text{Be}\) CE\(_{2}\)NS events.

A background control region with S2 < 120 PE contains \( >50\% \) of the AC background, and is excluded from the search for \(^{8}\text{Be}\) CE\(_{2}\)NS due to its low detection probability. After closer inspection of the candidate waveforms 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 \( < 5\% \) 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\(_{2}\)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 \( S_{2\text{prev}}/\Delta t_{\text{prev}} \).

![Graph](image)

**FIG. 2.** Events in the science dataset (pink circles) and the AC-enriched validation region (blue crosses) projected onto \( Z \) and the quantile of the \( S_{2\text{prev}}/\Delta t_{\text{prev}} \) value for NR signals. The AC model is shown in gray. Smaller panels show the projection of the model and data onto each axis, as well as the \(^{8}\text{Be}\) CE\(_{2}\)NS model (green dashed), normalized to its upper limit. The AC-enriched region data in blue has a slightly different \( Z \) distribution due to the inverted GBDT cut, but is included for illustration, scaled by 0.36, the ratio of expected AC events in each dataset.

Neutrons originating from radioimpurities inside detector materials produce NRs in the TPC, but the tight ROI reduces these to 0.039 \( ^{+0.002}_{-0.001} \) events. To limit the electronic recoil (ER) background dominated by \( \beta \) decays of \(^{214}\text{Pb} \) (a daughter of \(^{222}\text{Rn} \)), 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\(_{2}\)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, but is included in the background total. The last two columns show the result from the AC validation region, where the expectation value is dominated (97\%) by AC events, with the remainder from the expected \(^{8}\text{B} \) CE\( 2 \)NS leakage. The relative uncertainties on the background and signal expectations are described in the text.

<table>
<thead>
<tr>
<th>S1 hit properties</th>
<th>Science data</th>
<th></th>
<th>AC validation region</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hit category</td>
<td>LHA</td>
<td>AC</td>
<td>ER</td>
</tr>
<tr>
<td>2 Hits, 1+ in TA</td>
<td>≥2 PE</td>
<td>0.09</td>
<td>0.01</td>
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<td>0.09</td>
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<td>0.01</td>
</tr>
<tr>
<td></td>
<td>&lt;2 PE</td>
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<tr>
<td>Total</td>
<td></td>
<td>5.14</td>
<td>0.21</td>
</tr>
</tbody>
</table>

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

(1)

Here, \( \tilde{\theta} \) are the nuisance parameters. The extended unbinned likelihood terms \( L_i(\Phi, Q_y, L_y, \tilde{\theta}) \) are of the same form as Eq. (20) in Ref. [17], and include models in S2, Z, and \( S_2^\text{prev}/\Delta t^\text{prev} \) for the \(^{8}\text{B} \) CE\( 2 \)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\( 2 \)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\( 2 \)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\( 2 \)NS, DM, and the neutron background change both in shape and expectation value with \( Q_y \) and \( L_y \). The CE\( 2 \)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].

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\( 2 \)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\( 2 \)NS expectation value. Details on the construction of these confidence intervals may be found in the Supplemental Material [25].

By including external constraints on \( \Phi \), \( Q_y \), 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\( 2 \)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\( 2 \)NS cross section if we use the externally measured value of \( \Phi \). We also consider DM-nucleus interactions, including CE\( 2 \)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\( 2 \)NS excess in this data to be 20\% (50\%) for the nominal (NEST) values of \( Q_y \) and \( L_y \). 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\( 2 \)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. The XENON1T confidence interval in \( \Phi \), \( Q_y \), and \( L_y \) does not strongly constrain any of the parameters due to the significant correlation in particular between \( \Phi \) and \( L_y \), as
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 \( 4.4 \times 10^7 \) 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 \( e^{\nu}_d \) and \( e^{\nu}_c \), respectively \([3,34,35]\). The 90\% confidence interval for \( e^{\nu}_d \) and \( e^{\nu}_c \) 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.

\textbf{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

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig3.png}
\caption{Projections of the 90\% confidence volumes in \( L_y \) and \( \Phi \) (top), and in \( L_y \) and the \( Q_y \) interpolation parameter \( q \) (bottom). The green area shows constraints using only the XENON1T data. Combining the XENON1T data and external constraints on \( Q_y \) \([19]\) and \( L_y \) \([22,37]\) (shown in black dash-dotted lines) gives the confidence interval shown in pink, and an upper limit on \( \Phi \). Conversely, combining the XENON1T data and constraints on \( \Phi \) \([16]\) and \( Q_y \) yields the dark blue interval and upper limits on \( L_y \). The dashed white line displays the 68\% confidence interval. \( L_y \) is assumed constant in the \( ^8\)B CE\( \nu \)-NS ROI for these constraints.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig4.png}
\caption{Constraints on new physics using XENON1T data. Top: Constraints on nonstandard vector couplings between the electron neutrino and quarks, where the XENON1T 90\% confidence interval (light blue region) is compared with the results from COHERENT \([3,34]\) (pink and dark red regions) and CHARM \([38]\) (green). Bottom: The 90\% upper limit (blue line) on the spin-independent DM-nucleon cross section \( \sigma_{SI} \) as function of DM mass. Dark and light blue areas show the 1\(\sigma\) and 2\(\sigma\) sensitivity bands, and the dashed line the median sensitivity. Green lines show other XENON1T limits on \( \sigma_{SI} \) using the threefold tight-coincidence requirement \([8]\) and an analysis using only the ionization signal \([9]\), and other constraints \([39–44]\) are shown in red. The dash-dotted line shows where the probability of a 3\(\sigma\) DM discovery is 90\% for an idealized, extremely low-threshold (3 eV) xenon detector with a 1000 t \( \times \) y exposure \([45]\). The black dot denotes DM that has a recoil spectrum and rate identical to the \( ^8\)B neutrinos.}
\end{figure}
liquid circulation system developed to ensure efficient purification in XENON1T will mitigate the reduction of S2s due to impurities, improving the acceptance of low-energy NRs from $^8\text{B}$ 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 $^8\text{B}$ CE$_{\text{e}}$NS.

The large uncertainty in both $Q_1$ and $L_1$ 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 $^8\text{B}$ CE$_{\text{e}}$NS and light DM.

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