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First Dark Matter Search Results from the XENON1T Experiment

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We report the first dark matter search results from XENON1T, a ∼2000-kg-target-mass dual-phase (liquid-gas) xenon time projection chamber in operation at the Laboratori Nazionali del Gran Sasso in Italy and the first ton-scale detector of this kind. The blinded search used 34.2 live days of data acquired between November 2016 and January 2017. Inside the 1042 ± 12-kg fiducial mass and in the [5, 40] keVnr energy range of interest for weakly interacting massive particle (WIMP) dark matter searches, the electronic recoil background was (1.93 ± 0.25) × 10−4 events/(kg × d × keVnr), the lowest ever achieved in such a dark matter detector. A profile likelihood analysis shows that the data are consistent with the background-only...
Modern cosmology precisely describes observational data from the galactic to the cosmological scale with the Λ cold dark matter model [1,2]. This model requires a nonrelativistic nongeometric component of the Universe called dark matter, with an energy density of $\Omega_\Lambda h^2 = 0.1197 \pm 0.0022$ as measured by Planck [3]. Theories beyond the standard model of particle physics (e.g., supersymmetry [4]) often attribute this energy density to weakly interacting massive particles (WIMPs) that may be detectable by underground detectors [5,6].

The XENON1T experiment is designed primarily for detecting nuclear recoils (NRs) from WIMP-nucleus scattering, continuing the XENON program [7,8] that employs dual-phase (liquid-gas) xenon time projection chambers (TPCs) [8,9]. With a total mass of $\sim$3200 kg of ultrapure liquid xenon—more than 2 orders of magnitude larger than the initial detector of the XENON project [7]—XENON1T is the first detector of such scale realized to date. It is located at the Laboratori Nazionali del Gran Sasso in Italy, at an average depth of 3600 m water equivalent. The approximately 97-cm-long by 96-cm-wide cylindrical TPC encloses (2004 $\pm$ 5) kg of liquid xenon (LXe), while another $\sim$1200 kg provides additional shielding. The TPC is mounted at the center of a 9.6-m-diameter, 10-m-tall water tank to shield it from ambient radioactivity. An adjacent service building houses the xenon storage, cryogenics plant, data acquisition, and slow control system. The water tank is mounted with 84 photomultiplier tubes (PMTs) as part of a Cherenkov muon veto [10]. The TPC is instrumented with 248 3-in. Hamamatsu R11410-21 PMTs arranged in two arrays above and below the LXe target [11,12]. Interactions in the target produce scintillation photons (S1) and ionization electrons. The electrons drift in a $\gamma$-V/cm electric field toward the liquid-gas interface at the top of the TPC. They are extracted into the gas by an electric field $E_{\text{gas}} > 10$ kV/cm where, via electroluminescence, they produce a proportional scintillation signal (S2). This charge-to-light amplification allows for the detection of single electrons [13,14]. The ratio of the S2 to S1 signals is determined by both the ratio of ionization to excitation in the initial interaction and subsequent partial recombination of the ionization, with lower S2/S1 for NR signals than electronic recoils (ERs) from $\gamma$ and $\beta$ radiation.

Here, we report on 34.2 live days of blinded dark matter search data from the first science run of the experiment. The run started on November 22, 2016, and ended on January 18, 2017, when an earthquake temporarily interrupted detector operations. The detector’s temperature, pressure, and liquid level remained stable at (177.08 $\pm$ 0.04) K, (1.934 $\pm$ 0.001) bar, and (2.5 $\pm$ 0.2) mm respectively, where the liquid level was measured above the grounded electrode separating the drift and extraction field regions. While the PMT high voltage remained stable during the run, 27 PMTs were turned off for the dark matter search and 8 were masked in the analysis due to low single-photoelectron (PE) detection efficiency. The PMT response was calibrated periodically using pulsed light-emitting diode data [15]. The xenon was continuously purified in the gas phase through hot metal getters, leading to an increase in the electron lifetime from 350 to 500 $\mu$s, with an average of 452 $\mu$s; 673 $\mu$s is the drift time over the length of the TPC. Using cryogenic distillation [16], the Na$^+$Kr concentration in the LXe was reduced while the TPC was in operation, from (2.60 $\pm$ 0.05) ppt (mol/mol) at the beginning of the science run to (0.36 $\pm$ 0.06) ppt one month after the end of the science run, as measured by rare-gas mass spectrometry [17] on samples extracted from the detector. The $^{214}$Pb event rate was (0.8–1.9) $\times$ 10$^{-4}$ events/(kg × day × keVee) in the low-energy range of interest for WIMP searches, where the bounds are set using in situ a spectroscopy on $^{218}$Po and $^{214}$Po. The $^{222}$Rn concentration was reduced by $\sim$20% relative to the equilibrium value using the krypton distillation column in inverse mode [18].

The data acquisition (DAQ) system continuously recorded individual PMT signals. The efficiency for recording single-PE pulses was 92% on average during the science run, and stable to within 2%. A software trigger analyzed the PMT pulses in real time, allowing for continuous monitoring of the PMTs. The trigger detected $S2_s$ larger than 200 PE with 99% efficiency, and saved 1 ms before and after these to ensure that small NR hits were captured. An analog-sum waveform was separately digitized together with a signal recording when any of the digitizers were inhibited. The average DAQ live time was 92% during the science run. Physical signals are reconstructed from raw data by finding photon hits in each PMT channel, then clustering and classifying groups of hits as S1 or S2 using the PAX software. For S1s, we require that hits from three or more PMTs occur within 50 ns. To tune the signal reconstruction algorithms and compute their efficiency for detecting NRs—shown in blue in Fig. 1—we used a Monte Carlo code that reproduces the shapes of S1s and S2s as determined by the interaction physics, light propagation, and detector-electronics chain. This was validated against $^{83}$Kr and $^{220}$Rn calibration data. The interaction position is reconstructed from the top-array PMT hit pattern of the S2 (for the transverse position) and the time difference between S1 and S2 (for depth). The
S2 transverse position is given by maximizing a likelihood based on an optical simulation of the photons produced in the S2 amplification region. The simulation-derived transverse resolution is $\sim 2$ cm at our S2 analysis threshold of 200 PE (uncorrected). The interaction position is corrected for drift field nonuniformities derived from a finite element simulation, which is validated using $^{83}$mKr calibration data. We correct S2s for electron losses during drift, and both S1s and S2s for spatial variations of up to 30% and 15%, respectively, inferred from $^{83}$mKr calibration data. These spatial variations are mostly due to geometric light-collection effects. The resulting corrected quantities are called cS1 and cS2. As the bottom PMT array has a more homogeneous response to S2 light than the top, this analysis uses cS2_b, a quantity similar to cS2 based on the S2 signal seen only by the bottom PMTs.

To calibrate XENON1T, we acquired 3.0 days of data with $^{220}$Rn injected into the LXe (for low-energy ERs), 3.3 days with $^{83}$mKr injected into the LXe (for the spatial response) and 16.3 days with an external $^{241}$AmBe source (for low-energy NRs). The data from the $^{220}$Rn [19] and $^{241}$AmBe calibrations are shown in Figs. 2(a) and 2(b), respectively. Following the method described in Ref. [20] with a W value of 13.7 eV, we extracted the photon gain $g_1 = (0.144 \pm 0.007)$ PE per photon and the electron gain $g_2 = (11.5 \pm 0.8)$ PE (in the bottom array, 2.86 times lower than if both arrays are used) per electron in the fiducial mass by fitting the anticorrelation of cS2_b and cS1 for signals with known energy from $^{83}$mKr ($41.5$ keV), $^{60}$Co from detector materials ($1.173$ and $1.332$ MeV), and from decays of metastable $^{131}$mXe ($164$ keV) and $^{129}$mXe ($236$ keV) produced during the $^{241}$AmBe calibration. The cS1 and cS2_b yields are stable in time within 0.77% and 1.2%, respectively, as determined by the $^{83}$mKr calibrations.

WIMPs are expected to induce low-energy single-scatter NRs. Events that are not single scatters in the LXe are removed by several event-selection cuts: (1) a single S2 above 200 PE must be present and any other S2s must be compatible with single electrons from photoionization of impurities or delayed extraction; (2) an event must not closely follow a high-energy event (e.g., within $3 \times 10^5$ PE S2), which can cause long tails of single electrons; (3) the S2 signal’s duration must be consistent with the depth of the interaction as inferred from the drift time; (4) the S1 and S2 hit patterns must be consistent with...
the reconstructed position at which these signals were produced; (5) no more than 300 PE of uncorrelated single electrons and PMT dark counts must appear in the region before the S2. Single-scatter NR events within the [5, 40] keV$_{ee}$ energy range pass these selections with > 82% probability, as determined using simulated events or control samples derived from calibration, and shown in green in Fig. 1.

The dark matter search uses a cylindrical (1042 ± 12)-kg fiducial mass, which was defined before unblinding using the reconstructed spatial distribution of ERs in the dark matter search data and the energy distribution of ERs from $^{220}$Rn. We restrict the search to $cS1 \in [3, 70]$ PE and $cS2_b \in [50, 8000]$ PE, which causes little additional loss of WIMP signals, as shown in black in Fig. 1.

Table I lists the six sources of background we consider inside the fiducial mass and inside the search region. For illustration, we also list the expected rate in a reference region between the NR median and the $-2\sigma$ quantile in $cS2_b$ [i.e., between the red lines in Fig. 2(c)], for which Fig. 3 shows the background model projected onto $cS1$. This reference region would contain about half of the ERs is not constrained in the likelihood analysis, even though we have independent concentration measurements for $^{214}$Pb and $^{85}$Kr, since the most stringent constraint comes from the search data themselves.

Second and third, our background model includes two sources of NRs: radiogenic neutrons contribute (0.05 ± 0.01) events and coherent neutrino-nucleus scattering (CNNS) ~0.02 events. Cosmogenically produced neutrons are estimated to contribute $O(10^{-3})$ events even without muon-veto tagging. The NR background model is built from a detector response simulation that shares the same detector parameters and associated systematic uncertainties as the ER background model above. The main difference is the energy-conversion model, where we use the model and parametrization from NEST [22]. We obtain the XENON1T response to NRs by fitting the $^{241}$AmBe calibration data [Fig. 2(b)] with the light and charge yields from Ref. [22] as priors. Our NR response model is therefore constrained by the global fit of external data. It is also used to predict the WIMP signal models in ($cS1$, $cS2_b$) space. The $S1$ detection efficiency, which is responsible for our low-energy threshold, is consistent with its prior (0.7$\sigma$).

Fourth, accidental coincidences of uncorrelated $S1$s and $S2$s are expected to contribute (0.22 ± 0.01) background events. We estimated their rate and ($cS1$, $cS2_b$) distribution using isolated $S1$ and $S2$ signals, which are observed to be at (0.78 ± 0.01) Hz and (3.23 ± 0.03) mHz, respectively, before applying $S2$ selections. The effect of our event selection on the accidental coincidence rate is included.

![FIG. 3. Background model in the fiducial mass in a reference region between the NR median and the $-2\sigma$ quantile in $cS2_b$, projected onto $cS1$. Solid lines show that the expected number of events from individual components listed in Table I; the labels match the abbreviations shown in the table. The dotted black line “Total” shows the total background model, while the dotted red line “WIMP” shows an $\sigma = 10^{-46}$ cm$^2$ WIMP signal for comparison.](image-url)

TABLE I. Expected number of events for each background component in the fiducial mass; in the full $cS1 \in [3, 70]$ PE, $cS2_b \in [50, 8000]$ PE search region and in a reference region between the NR median and the $-2\sigma$ quantile in $cS2_b$. Uncertainties < 0.005 events are omitted. The ER rate is unconstrained in the likelihood; for illustration, we list the best-fit values to the data in parentheses.

<table>
<thead>
<tr>
<th>Component</th>
<th>Full</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electronic recoils (ERs)</td>
<td>(62 ± 8)</td>
<td>(0.26$^{+0.11}_{-0.07}$)</td>
</tr>
<tr>
<td>Radiogenic neutrons ($n$)</td>
<td>0.05 ± 0.01</td>
<td>0.02</td>
</tr>
<tr>
<td>CNNS ($\nu$)</td>
<td>0.02</td>
<td>0.01</td>
</tr>
<tr>
<td>Accidental coincidences (acc)</td>
<td>0.22 ± 0.01</td>
<td>0.06</td>
</tr>
<tr>
<td>Wall leakage (wall)</td>
<td>0.5 ± 0.3</td>
<td>0.01</td>
</tr>
<tr>
<td>Anomalous (anom)</td>
<td>0.10$^{+0.10}_{-0.07}$</td>
<td>0.01 ± 0.01</td>
</tr>
<tr>
<td>Total background</td>
<td>63 ± 8</td>
<td>0.36$^{+0.11}_{-0.07}$</td>
</tr>
<tr>
<td>50-GeV/c$^2$, 10$^{-46}$-cm$^2$ WIMP</td>
<td>1.66 ± 0.01</td>
<td>0.82 ± 0.06</td>
</tr>
</tbody>
</table>
similar to Ref. [23]. Isolated S1s may arise from interactions in regions of the detector with poor charge collection, such as below the cathode, suppressing an associated cS2 signal. Isolated S2s might arise from photoionization at the electrodes, from regions with poor light collection, or from delayed extraction [24]. Most accidental events are expected at low cS1 and at lower cS2b than at typical NRs.

Fifth, inward-reconstructed events from near the TPC’s polytetrafluoroethylene wall are expected to contribute \((0.5 \pm 0.3)\) events, with the rate and \((cS1, cS2b)\) spectrum extrapolated from events outside the fiducial mass. Most of these events would appear at unusually low cS2b due to charge losses near the wall. The inward reconstruction is due to limited position reconstruction resolution, limited especially for small S2s, near the 5 (out of 36) top PMTs in the outermost ring that are unavailable in this analysis.

Sixth and last, we add a small uniform background in the \((cS1, \log cS2b)\) space for ER events with an anomalous \(cS2b\). Such anomalous leakage beyond accidental coincidences was observed in XENON100 [23], and one such event is seen in the \(^{220}\text{Rn}\) calibration data [Fig. 2(a)]. If these were not \(^{220}\text{Rn}\)-induced events, their rate would scale with exposure and we would see numerous such events in the WIMP search data. We do not observe this and therefore assume their rate is proportional to the ER rate, at \(0.10^{0.10}_{-0.07}\) events based on the outliers observed in the \(^{220}\text{Rn}\) calibration data. The physical origin of these events is under investigation.

The WIMP search data in a predefined signal box were blinded (99% of ERs were accessible) until the event selection and the fiducial mass boundaries were finalized. We performed a staged unblinding, starting with an exposure of four live days distributed evenly throughout the search period. No changes to either the event-selection or background types were made at any stage.

A total of 63 events in the 34.2-day dark matter search data pass the selection criteria and are within the \(cS1 \in [3, 70]\) PE, \(cS2b \in [50, 8000]\) PE search region used in the likelihood analysis [Fig. 2(c)]. None are within 10 ms of a muon-veto trigger. The data are compatible with the ER energy spectrum in Ref. [9] and implies an ER rate of \((1.93 \pm 0.25) \times 10^{-4}\) events/(kg \(\times\) day \(\times\) keV\(\text{ee}\)), compatible with our prediction of \((2.3 \pm 0.2) \times 10^{-4}\) events/(kg \(\times\) day \(\times\) keV\(\text{ee}\)) [9] updated with the lower Kr concentration measured in the current science run. This is the lowest ER background ever achieved in such a dark matter experiment. A single event far from the bulk distribution was observed at \(cS1 = 68.0\) PE in the initial 4-day unblinding stage. This appears to be a bona fide event, though its location in \((cS1, cS2b)\) [see Fig. 2(c)] is extreme for all WIMP signal models and background models other than anomalous leakage and accidental coincidence. One event at \(cS1 = 26.7\) PE is at the \(-2.4\sigma\) ER quantile.

For the statistical interpretation of the results, we use an extended unbinned profile likelihood test statistic in \((cS1, cS2b)\). We propagate the uncertainties on the most significant shape parameters (two for NR, two for ER) inferred from the priors of the calibration fits to the likelihood. The uncertainties on the rate of each background component mentioned above are also included. The likelihood ratio distribution is approximated by its asymptotic distribution [25]; preliminary toy Monte Carlo checks show that the effect on the exclusion significance of this conventional approximation is well within the result’s statistical and systematic uncertainties. To account for mismodeling of the ER background, we also calculated the limit using the procedure in Ref. [26], which yields a similar result.

The data are consistent with the background-only hypothesis. Figure 4 shows the 90% confidence level upper limit on the spin-independent WIMP-nucleon cross section, power constrained at the \(-1\sigma\) level of the sensitivity band [29]. The final limit is within 10% of the unconstrained limit for all WIMP masses. For the WIMP energy spectrum, we assume a standard isothermal WIMP halo with \(v_0 = 220\) km/s, \(\rho_{\text{DM}} = 0.3\) GeV/cm\(^3\), \(v_{\text{esc}} = 544\) km/s, and the Helm form factor for the nuclear cross section [30]. No light or charge emission is assumed for WIMPs below 1-keV recoil energy. For all WIMP masses, the background-only hypothesis provides the best fit, with none of the nuisance parameters representing the uncertainties discussed above deviating appreciably from their nominal values. Our results improve upon the previously strongest spin-independent WIMP limit for masses above 10 GeV/c\(^2\). Our strongest exclusion limit is for 35-GeV/c\(^2\) WIMPs, at \(7.7 \times 10^{-47}\) cm\(^3\).

These first results demonstrate that XENON1T has the lowest low-energy background level ever achieved by a
dark matter experiment. The sensitivity of XENON1T is the best to date above 20 GeV/c², up to twice the LUX sensitivity above 100 GeV/c², and continues to improve with more data. The experiment resumed operation shortly after the January 18, 2017, earthquake and continues to record data.

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