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Review of background study in S2-only analysis in XENON1T experiment

Y. Pan

LPNHE, Sorbonne Université, Université de Paris, CNRS/IN2P3 - Paris, France

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Summary. — The XENON1T experiment is a direct dark matter detection experiment in the form of weakly interacting particles (WIMPs) scattering off nuclei. Without requiring a scintillation signal, we can set constraints on light dark matter (DM) models using only the ionization signals. This paper reviews the background study done in S2-only analysis in XENON1T experiment. We developed a strong data selection to identify three background components: low-energy β decays on the cathode wires, coherent nuclear scattering of ^{8}B solar neutrinos (CEvNS) and electron recoil (ER) from high Q-value β decays.

1. – Introduction

A large number of astrophysical observations [1] have demonstrated the existence of a non-luminous component of massive dark matter (DM) beyond Standard Model, making up about 26% of the mass-energy of the universe. Weakly interacting massive particles (WIMPs) are among the most well-motivated dark matter candidates [2].

The XENON1T experiment [3] at the INFN Laboratori Nazionali del Gran Sasso (Italy) focuses on searching for weakly interacting massive particles (WIMPs) scattering elastically off xenon atoms. XENON1T is a dual-phase time projection chamber (TPC) operated with a total of ~ 3.2 tonnes of ultra-pure liquid Xe (LXe) with 2 tonnes as the active target. The TPC is cylindrical in shape, 96 cm in diameter and 97 cm in height. The top and bottom surfaces are fitted with 248 Hamamatsu 3" photomultiplier tube (PMT) arrays [4, 5].

The observable signals are the scintillation (S1) and ionization (S2) signals from energy depositions. S2 signal is produced by electroluminescence in gaseous xenon from electrons drifted upwards under an electric field, and got extracted from the liquid into the gas. The longitudinal (z) position is reconstructed using the time difference between the prompt S1 signal and the S2 signal. The position in the (x,y) plane is reconstructed by the S2 signal pattern in the upper PMT array. In addition, the S2/S1 ratio can be used to distinguish between nuclear recoils (NRs) from WIMPs and neutrons, as well as electron recoils (ERs) from γ and β, which constitute the main background of the XENON1T experiment [3].

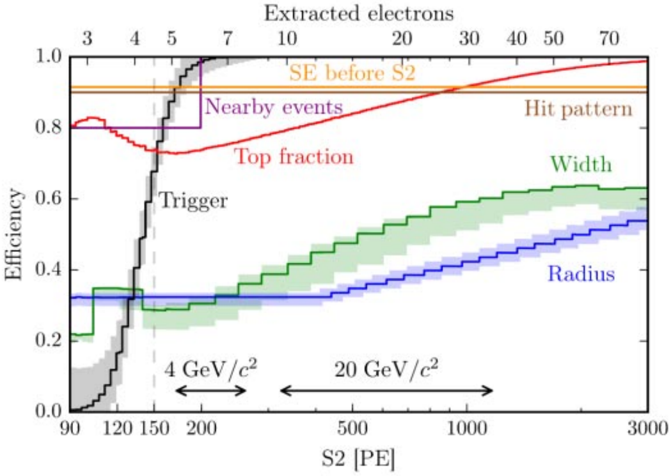

Fig. 1. – Efficiency of main event selection (fraction of events passed) *versus* S2 size. Solid lines bands to the ± 1σ variation of the model parameters. The arrows indicate the S2 ROI for the 4 and 20 GeV c^{-2} spin-independent NR DM analyses. The top horizontal axis shows the corresponding number of extracted electrons to S2 [8].

2. – Data selection

Dual-phase LXe TPCs are most sensitive to DM with masses mχ $\geq$ 6 GeV c^{-2}, as lighter DM is unable to transfer enough energy ($\sim$ 3.5 keV) to xenon nuclei to produce detectable S1 at a sufficient rate. However, with the ionization signals S2s by secondary scintillation, particles transferring as low as 0.7 keV for nuclear recoils and 0.186 keV for electronic recoils can be detected [6]. Here, "S2-only analysis" refers to the reanalysis of XENON1T's data without S1s.

We use the main science run (SR1) of XENON1T [7] with a live time of 258.2 days. We use 30% of the SR1 events as training data, uniformly distributed in time, to determine event selection and to identify a region of interest (ROI) of integrated S2 charge for each dark matter model and mass. Only the remaining 70% (search data, 180.7 days) is used to calculate the limits of the DM parameters. We choose a selection set to remove identifiable background components for different DM models.

Figure 1 shows the efficiencies of the most impactful cuts with S2 size. Without S1, it is difficult to accurately estimate the event depth z. However, the width of S2 waveform in time is correlated with z due to the diffusion of electrons during the drift. The events with S2 widths larger than 835 ns are excluded to eliminate the β decays occurring on the cathode wires as they have unusually small S2 due to charge loss. Many have detectable S1 and can be easily removed by depth related cuts on with S1 [8]. Similarly, width cut can suppress the events from decay on the electrodes at the top of the TPC with atypically narrow S2 width. The width cut efficiency is calculated with simulated S2 waveforms, which show agreement with those observed in deuterium-deuterium plasma fusion neutron generator calibration data [9]. We also remove events reconstructed at high radii R which are with unusually small S2 due to the charge loss on TPC walls. Its efficiency is estimated using $^{83\mathrm{m}}$Kr calibration data. The top fraction cut is to remove events constituted by more than 66% light from the top PMT array which is normally

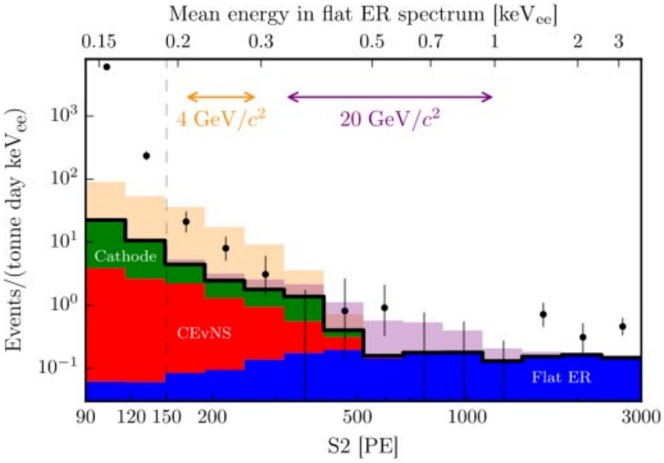

Fig. 2. – Distribution of events passing all cuts (black dots); error bars show statistical 1σ uncertainties. The thick black line shows the summed background model consisting of three components. The light orange (purple) histogram shows the signal model for the 4 GeV c^{-2} (20 GeV c^{-2}) DM model excluded at 90% confidence level. The arrows show the ROIs. The top x-axis indicates the average energy of the after-cuts events [8].

events in gaseous phase. The efficiency is calculated from binomial fluctuations in photon detection [8].

Pileup of randomly emitted single-electron (SE) signals contributes to the background in S2-only analysis, originating from electrons trapped at the interface and electrons captured by electronegative impurities (*e.g.*, O_2) in the liquid xenon. This population can be removed by three cuts. Firstly, their S2 hit pattern is inconsistent with that of the single scattering. The related cut has a 90% efficiency measured with neutron generator data. Secondly, “SE before S2 cut” is to exclude single electron (SE) signals up to $\sim$ 1 ms before the largest S2 which can also suppress gas events with broader S1 and therefore often misidentified as S2. Thirdly, “Nearby events cut” can reduce the enhanced SE emission close in time and position to high energy events [10].

3. – Background characterization

The best-fit detector response model from ref. [11] is used, setting the detection threshold as 0.7 keV for NRs and as 186 eV for ERs, as the LXe charge yield Qy has never been measured below these energies [8]. While we do not have access to a complete model for S2-only analysis, we can quantify the three components of the background and compare the observed events to our nominal signal and background models, as shown in fig. 2. The first one is the ER background from high Q-value β decays, mainly ^{214}Pb, is flat in our energy range of interest. The second one is coherent nuclear scattering of ^{8}B solar neutrinos (CEvNS). The third one is from low-energy β decays on the cathode wires. For S2 $\geq$ 300 PE ($\sim$ 0.3 keVee), we observe rates well below 1 /(tonne·day·keVee), while below 150 PE the rate rises rapidly, which may be due to the unknown background.

4. – Conclusion

The background of few electrons S2 signals in XENON1T is investigated. We attributed this background to impurities within the LXe target volume. A strong data selection criteria optimizes the signal-to-noise ratio of the XENON1T ionization signal. Above 0.4 keVee, < 1 /(tonne·day·keVee) event is observed.

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