Latest results from the XENON1T experiment

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Abstract. The most successful class of direct detection of WIMPs with masses from few GeV/c^2 to TeV/c^2 have utilized Liquid Xenon time projection chambers (TPCs). The XENON project adopted dual phase TPCs using ultra-pure liquid Xenon as both target and detection medium for WIMPs. The first ton-scale Liquid Xenon based TPC, XENON1T, is running at the Gran Sasso Laboratory. With an active mass inside the TPC of 2 tonnes, data were collected for 278.8 days live time. Within a fiducial mass of 1.3 tonne, this results in 1.0 tonne × year exposure. In the energy region of interest, the detector exhibits the lowest background ever obtained in direct dark matter search experiment. In these data no significant excess over background is found and the most stringent limits on WIMP-nucleon spin-independent elastic scattering cross section has been set for masses above 6 GeV/c^2 with a minimum of 4.1 × 10^{-47} cm^2 at 30 GeV/c^2.

1. Introduction

It is evident from models and astronomical observations that the current energy density of the universe is made out of 5% quarks and leptons, 25% of Dark Matter (DM) and the rest dark energy. In the early 1930 DM was proposed as an unknown additional kind of matter that would reconcile the observation of the velocity of Coma cluster with respect to calculations. Strong evidences, for the existence of DM, follow after using astronomical observations based on its interaction gravitationally with baryonic matter. But up to today the nature of DM is not revealed yet. Theories beyond the standard model of particle physics predict the existence of DM particles. Weakly Interacting Massive Particles (WIMPs) are the most popular in these theories. They are supposed to be moving with non-relativistic velocities, thus they are cold DM.

2. Direct searches for WIMPs

Two distinct detection techniques exist to search for WIMPs. The indirect one relies on the fact that WIMPs can be trapped gravitationally in the core of dense objects, like the sun, and then self-annihilate into standard model particles. The second, the direct search, assumes a scattering of the WIMP on nucleus inside a detector. The recoil of the target nucleus will rise ionization signals as the WIMP move through the detector medium. Depending on the detector medium, in the case of scintillators like Liquid Xenon (LXe), the passage of WIMPs generate both ionization and scintillation signals. To search for WIMPs the Xenon collaboration adopted the dual phase Time Projection Chamber (TPC) technique. This latter proved to be the highest sensitive among other search techniques for WIMP mass $m_\chi > 6$ GeV/c^2[1].
3. The XENON1T detector

The XENON project at the INFN Laboratori Nationali del Gran Sasso (LNGS), developed three detectors using three different masses of LXe. The project starts with XENON10, which had as a total target mass about 15 kg of LXe. After its success in terms of sensitivity to the Spin-Independent (SI) WIMP-nucleon cross section, the target mass had been increased by about factor 4, i.e. XENON100. The XENON collaboration is now operating XENON1T, which contains 3.2 tonnes of ultra-pure LXe and reached a sensitivity that is one order of magnitude better than the one obtained with the XENON100 detector [3]. The XENON1T detector is located at an average depth of 3600 m water-equivalent at LNGS to minimize the cosmic rays background.

Figure 1 shows a sketch of the working principle of LXe TPC. The XENON1T detector is made out of stainless steel double-wall cryostat surrounded with a water tank that acts as water Cherenkov muon veto system. The cryostat contains a TPC that hosts both LXe, acting as a target, and Gas Xenon (GXe). This LXe TPC is the largest one ever build to today, it contains 3.2 t of LXe and 2 t are used as the target active mass. It has a diameter of 96 cm and a height of 97 cm surrounded from above and below with 127 and 121 3” PMT arrays respectively [1, 2].

Figure 1. A sketch of the detection mechanism of an event in dual phase TPC. An interaction of a particle with the LXe atoms produces electrons and scintillation light. Electrons under the influence of the electric field drift upward and produces scintillation light in the gas phase while being accelerated further by a stronger electric field. The light detected by the PMTs in the upper part is called S2. The scintillation light called S1 is registered by the PMTs in the bottom part. The hit pattern of S2 gives the x-y position of the interaction point, while the time difference between S1 and S2 gives the z-position. Thus the dual phase TPC allows for a full determination of the 3D position of the vertex.

When a particle moves through the LXe volume, it interacts with its atoms producing a prompt scintillation light called S1 and also ionizes the medium. Electrons resulting from the ionization drift upward under the influence of the electric field of the TPC. At the interface Liquid-Gas, the electrons face another strong electric field, where they are extracted in the GXe phase. Thus producing the secondary scintillation light called S2. Both S1 and S2 are detected by the top and bottom arrays of PMTs respectively. The hit pattern of the detected S2 signal in the top PMTs gives the information about the vertex position in the x-y plane. The vertex position along the z-coordinate is deduced from the time difference between the S1 and S2 signals. Although LXe has an intrinsic self shielding capabilities, the vertex position of the interaction in 3D gives an extra parameter to reduce the background by selecting an inner volume called the fiducial volume. To further discriminate between Electronic Recoils (ER) and...
Nuclear Recoils (NR) for DM searches, the ratio of both S1 and S2 is used as an additional background discrimination parameter.

4. Data collection and analysis

The presented data are based on 32.1 days taken between November 22, 2016 and January 18, 2017, called Science Run 0 (SR0) [4]. In addition, another 246.7 days of data were taken from February 2, 2017 to February 8, 2018 called SR1 [3]. During the life time of both SR0 and SR1 the main detector parameters, the LXe level and the GXe pressure, were monitored continuously and found to be stable within an RMS of less than 0.02%. Also, an extensive regular calibration campaign of the detector has been taken. To monitor the stability of light yield, charge yield and electron life time, an internal source of $^{83}$mKr has been used. Another internal source, $^{220}$Rn, has been deployed to monitor and study the low energy part of the ER spectrum [5]. To calibrate the detector for NR, the collaboration used both, an external source of AmBe and a neutron generator [6].

The gain of the PMTs was also calibrated weekly using pulsed LED. Due to the position dependence of the light collection efficiency (LCE), the S1 signal is corrected ($c_{S1}$). The S2 signal is corrected for both the electron life time (which was 380 µs for SR0 and reach about 650 µs for SR1) in addition a correction ($c_{S2_b}$) for position dependence of LCE. The bottom PMTs are used to estimate also the energy of S2 after correction $c_{S2_b}$ due to a more homogeneity of the LCE at the bottom.

The data, in both SR0 and SR1, were blinded in the signal region above the S2 threshold of 200 PE and below the ER-2σ in ($c_{S1}$, $c_{S2_b}$) space initially. All events are required to have a valid S1 and S2 pair, where S1 is required to have at least a coincidence signals from 3 PMTs within 100 ns. The energy region of interest is defined in the range 3 and 70 PE in terms of $c_{S1}$, which corresponds to an average [1.4, 10.6] keVee (ER energy) or [4.9,40.9] keVnr (NR energy). The data analysis is based on $c_{S1}$, $c_{S2_b}$, the radial distance $R$ and $Z$. In addition every possible background component is modeled as probability density function of all analysis dimensions including the WIMP NR signal. The remaining data in the fiducial mass of 1.3 tons are interpreted using an unbinned extended likelihood with profiling over nuisance parameters [3].

After unblinding the total number of NR events remaining was found to be consistant with the background expectations. The profile likelihood analysis indicates no significant excess in the 1.3 tons fiducial mass at any WIMP mass. Figure 2 shows the resulting 90% confidence level upper limit on Spin-Independent cross section, i.e. $\sigma_{SI}$, which falls within the predicted sensitivity range across all masses [3]. Moreover, the median sensitivity of this search is $\approx 7$ times
better than previous experiments, LUX [7] and PandaX-II[8], at WIMP masses above 50 GeV/c².

In summary, the XENON1T experiment found no significant excess above the background and set an upper limit on $\sigma_{SI}$ at $4.1 \times 10^{-47}$ cm² for a mass of 30 GeV/c², the most stringent limit to date for WIMP masses above 6 GeV/c².

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