Status of the XENON1T Dark Matter Search

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The XENON1T experiment is under construction at the Laboratori Nazionali del Gran Sasso in Italy. Building on an extremely successful program pioneered by the XENON10 and XENON100 experiments, XENON1T will provide the most sensitive measurement of the spin-independent WIMP-nucleon cross section to date, reaching sensitivities down to $2 \times 10^{-47}\mathrm{cm}^2$ after two years of data taking. We report on the design of the experiment as well as the current status of construction. The commissioning phase of XENON1T is expected to start in early 2015.

1 Dark Matter

Dark matter is postulated to be a new form of non-luminous matter that interacts very weakly with visible matter [1]. To date there is no direct evidence of the existence of dark matter particles. However there exists a wealth of indirect evidence that makes the inference of some of the properties of dark matter possible. This evidence includes the rotation curves of galaxies, the interaction of galaxy clusters, gravitational lensing measurements of galactic collisions, and precision measurements of the cosmic microwave background.

Several interpretations have been suggested to explain these and other observations including axions, sterile neutrinos, and weakly interacting massive particles (WIMPs) [2]. The WIMP is a particularly attractive candidate and is the main subject of the XENON1T experiment.

The hypothesized WIMP would be a new type of stable particle with a sizable mass and weak-scale interactions with normal matter and other WIMPs. In addition to the tiny interaction cross section this particle would interact with normal matter through gravity, providing explanations for many anomalous astrophysical observations.

The explanation of the dark matter phenomenon is one of the most important open questions in physics and has led to a worldwide hunt for the dark matter particle in which the XENON collaboration is taking a leading role [3].

2 The XENON1T Experiment

The search for an unknown particle with an extremely weak interaction cross section requires both an incredibly sensitive detector and very low background conditions. The XENON1T experiment is under construction at the Laboratori Nazionali del Gran Sasso (LNGS) in Italy.

This laboratory is built under 1400 m (3600 meters water equivalent) of rock, providing a factor of 10^6 reduction in the muon flux compared to the surface.

The XENON1T detector itself follows a scaled up design of the successful XENON10 [4] and XENON100 [5] detectors and is a dual-phase liquid xenon time projection chamber (TPC). XENON1T contains 3.3 tons (2.0 tons active volume) of high-purity liquid xenon instrumented from both above and below with low-background photomultiplier tubes. The volume is kept under a homogeneous electric field of about 1.0 kV/cm causing electrons freed in an interaction to drift towards the top of the TPC.

If an incoming WIMP interacts with a nucleus in the target volume it will produce both scintillation light (S1) and ionization electrons (S2). S1 signals are detected immediately while S2 signals are delayed due to the drift time of the electrons. The S2 is detected via proportional scintillation in the gas phase above the liquid target and provides a localized signal, allowing reconstruction of the (x,y) position of the interaction. The z position of the collision is derived from the time difference between the S1 and the S2.

WIMPs are expected to interact with the xenon nuclei while most background reactions interact with the electrons surrounding the nucleus. Liquid xenon TPCs provide excellent discrimination of electronic and nuclear collisions. The ratio of the charge (S2) to light (S1) signal is different for both collision types, allowing them to be separated in the analysis. During operation the detector is repeatedly calibrated using both gamma and neutron sources in order to study the detector response to electronic and nuclear recoils, respectively. The actual dark matter data is kept blinded in the signal region during the analysis.

A noteworthy aspect of a liquid xenon TPC is liquid xenon's excellent self-shielding capability. Because it is so dense the outer volume of xenon effectively shields the inner volume from background interactions originating from outside the TPC. However for WIMPs this effect is negligible. Therefore when performing the analysis only an inner fiducial volume of xenon is selected. The dimensions of this volume are optimized by studying the expected background distribution. A 10 cm fiducial cut in XENON1T will translate to a fiducial mass of ~ 1 ton.

3 Technical Developments and Sensitivity

Each iteration of the XENON experiment has been designed to provide about two orders of magnitude increase in sensitivity. To build a more sensitive liquid xenon TPC two things are required: a larger target mass and lower background levels. Realizing both of these features has been the subject of a continuous intensive research and development campaign performed by the XENON Collaboration.

A larger target mass provides obvious benefits on sensitivity and self-shielding. However creating a functional TPC with arbitrarily large size is not trivial. For XENON1T the main challenge was providing a stable 1.0 kV/cm electric field over a drift distance of 1m. This has been demonstrated using the XENON1T demonstrator, a 1m long TPC containing up to 60 kg of xenon in operation at Columbia University [9]. The development of this large-scale test apparatus has also allowed tests of the cryogenic and circulation systems.

The best sensitivity in a low-rate counting experiment is achieved with zero background, so the goal for XENON1T is to keep the background as close to zero as possible. One source of nuclear recoil backgrounds originate from cosmic muons which produce neutrons as secondary products as they pass near the detector. Though the muon flux is already very low at LNGS, muon induced neutrons could still cause a sizable background in the signal region. For this reason the XENON1T detector is surrounded by a 10m by 10m water Cerenkov detector [6]. When this detector sees a signal from a passing muon the data surrounding this signal will be vetoed. This reduces the muon induced background to negligible levels (about 0.01 events/year).

Radiogenic backgrounds provide the largest challenge to a low background experiment like XENON1T. Every detector component is a potential source of radiation. Radiogenic background from within the underground cavern are effectively reduced by the passive shielding provided by the water tank and the outer volume of xenon. To keep background originating from detector components low, a comprehensive material screening campaign is being performed in order to choose the most radio pure raw materials for the detector construction. The stainless steel used to construct the cryostat and parts of the TPC was specially selected by screening many samples. Special low background photomultiplier tubes from Hammamatsu have been manufactured using carefully selected components and extensively tested [7, 8]. A minimalist approach has been undertaken on the design and construction on the detector side in order to keep material, and thus material-induced backgrounds, to a minimum. Some background from the detector materials is unavoidable and so each component used in the construction of the detector has been carefully measured using high purity germanium detectors in order to provide an accurate background prediction for simulations. The predicted background from material contamination in the WIMP search region is about 0.25 events/year.

Other backgrounds come from the xenon itself. When ultra-pure xenon is ordered from a manufacturer it contains krypton as a contaminant on the ppb level. The unstable isotope ^{85}Kr comprises only a factor of $\sim 10^{-11}$ of natural krypton but its β-decays cause a significant background for a dark matter detector. Such impurities within the xenon volume itself are not rejected by fiducialization or analysis and must be removed physically. For XENON1T a krypton distillation column is used to remove krypton impurities from the xenon. This reduces levels of krypton to below the ppt level (target 0.5×10^{-12} Kr/Xe). Electronegative impurities such as O_2, N_2, and H_2O are filtered using getters. A predicted background of 0.15 events/year in the WIMP search region originates from impurities in the xenon.

Two final sources of irreducible background are the solar neutrino background and the double beta decay of ^{136}Xe (about 10% of natural xenon). Both of these backgrounds together contribute an estimated 0.09 events/year, making the full background prediction from all sources about 0.5 events/year.

The expected sensitivity of the XENON1T experiment has been computed with realistic assumptions on the detector performance and analysis efficiency. The background estimates provided above make the assumption that the XENON1T analysis will have similar acceptance and background rejection to the XENON100 analysis. The assumptions are a one ton fiducial volume, 5-50 keV search window for nuclear recoils, rejection of 99.5% of electonic recoil events, and acceptance of 50% of nuclear recoil events. The sensitivity to the spin-independent WIMP-nucleon cross section is shown in Figure 1.

4 Conclusion and Beyond XENON1T

XENON1T will be the most sensitive dark matter experiment in the world when it is completed in 2015. The detector sensitivity depends strongly on the target mass and XENON1T will reach its design sensitivity after two years of stable operation. For this reason a plan has been developed to reuse most of the detector installation to house a TPC with a larger volume of active xenon.

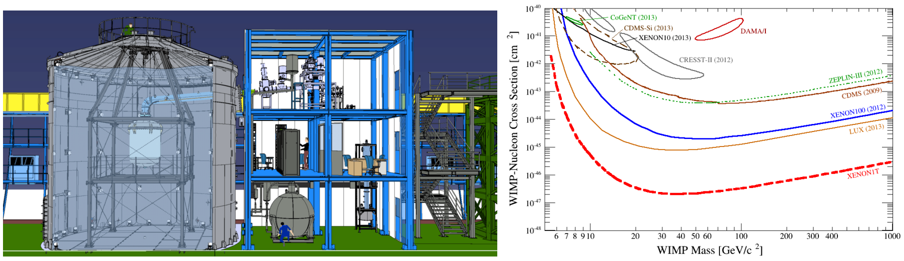

Figure 1: Left: a drawing of the XENON1T facility. Right: the projected spin-independent WIMP-nucleon cross section sensitivity compared to some existing experiments.

The XENONnT project will contain about 7 tons of xenon and has to goal of 20 ton-years of exposure. This will allow a sensitivity down to 10^{-48}cm^2 in the spin-independent WIMP-nucleon cross section. Development and construction will run in parallel to the operation of XENON1T with installation starting as early as 2018.

The main cost of the experiment will be procurement of additional xenon and photodetectors. However the large physical installations at the XENON1T facility have been designed to accomodate the new detector without modification. A new inner vessel will fit within the existing outer cryostat within the existing water tank. Signal and high voltage cables for the new photodetectors have already been installed within the cable pipes connecting the detector to the outside electronics and the existing DAQ, slow control, and computing infrastructure will be reused. The cryogenic and purification systems will also be repurposed for the operation of the new detector.

The XENON1T experiment itself is under construction at Gran Sasso. It is currently on schedule with commissioning planned for early 2015 and first results for later that year. With XENON1T and the planned upgrade, the XENON collaboration plans to remain at the forefront of WIMP direct detection.

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