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The next generation dark matter hunter: XENON1T status and perspective

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Abstract. The XENON Dark Matter Experiment has been ongoing at LNGS since 2005 with the goal of searching for dark matter WIMPs with liquid xenon as target and detector material. With detectors of increasing target mass and decreasing background, the XENON program has achieved competitive limits on WIMP-nucleon interaction couplings, but also on axions and axion like particles. With the start of the next generation experiment, XENON1T expected in 2015, XENON Dark Matter Experiment will continue to lead field of dark matter direct detection. XENON1T will be the first experiment to use multi-tons of liquid xenon in a time projection chamber and is designed to achieve two orders of magnitude higher sensitivity than the current best limits. I will review the status of construction and the scientific goals of XENON1T.

1. Introduction

There is an increasing number of astrophysical and astronomical observations pointing to the existence of a non-luminous, non-baryonic and cold (i.e. non-relativistic) matter component in the universe, called Cold Dark Matter (CDM) [1, 2]. The most appealing candidates for CDM are Weakly Interactive Massive Particles (WIMPs) predicted by supersymmetric theories (SUSY), models with extra dimensions and little Higgs models [3–5].

The XENON project is currently one the most promising experiments for the direct detection of dark matter. After the successful results of the first 10 and 100 kg scale liquid xenon detectors, XENON10 and XENON100 [6], the XENON project will continue to lead the field of worldwide direct dark matter experiments with its multi-ton liquid xenon detector called XENON1T, which will have an expected sensitivity to the spin-independent WIMP-nucleon cross section of 2×10^{-47} cm^2.

2. The XENON1T experiment

The construction of XENON1T started in 2013 at the Laboratori Nazionali del Gran Sasso (LNGS) in Italy, and it is expected to enter its first commissioning phase by Summer 2015. A drawing of the XENON1T facility is shown on Fig. 1.

The core of the detector (like its predecessors XENON10 and XENON100) is a dual-phase liquid xenon time projection chamber (TPC), which detection principle can be summarized as follows: if an incoming particle interacts with a nucleus in the target volume, it will produce both scintillation light, and ionization electrons. These last ones are drifted by an applied electric field towards the gas phase above the liquid, producing proportional

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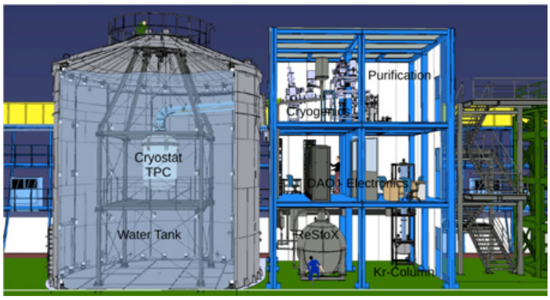

Figure 1. Sketch of the XENON1T facility. On the left the the water tank with inside the cryostat which holds the TPC; on the right the service building with the different detector subsystems: on the ground floor ReStoX and Kr-Column, on the first floor DAQ and Electronics and on the second floor Cryogenics and Purification.

light. The scintillation light (S1 signal) is promptly detected, while the proportional light (S2 signal) is delayed due to the drift time of the electrons. Being the S2 a localized signal, it allows the reconstruction of the (x,y) position of the interaction; the z position can be then derived from the time difference between the S1 and the S2 signals.

The discrimination principle between hypothetical signal (WIMP) and background particle starts from the different targets they are supposed to interact: nuclei for WIMPs and electrons that surround nuclei for most background. Nuclear and electron interactions have then different ratio of the S2 over S1 signal, thus allowing their separation via offline analysis. The study of the detector response to nuclear and electronic interactions will be achieved via calibration campaigns, with neutron and gamma sources respectively.

The XENON1T detector will contain ∼3.3 tons of high-purity liquid xenon (∼2 tons of which as active volume inside TPC), which provides excellent discrimination of electronic and nuclear interaction. Other remarkable property of liquid xenon is its self-shielding capability: the outer volume of xenon effectively shields the inner volume from background interactions occurring outside the TPC. This last one will be instrumented from both above and below with a total of 248 low-background photomultiplier tubes (PMT), and its volume will be kept under a homogeneous electric field $E_d > 500\,\mathrm{V/cm}$ over a drift distance of 1m.

To store and recovery the xenon a system called ReStoX will run in XENON1T, it was installed on August 2014 (see Fig. 2). It is a double-walled stainless steel sphere of 2.1m diameter capable to store xenon in different thermal conditions, even in different phases, depending on the needs, under high purity conditions. For this purpose it is well insulated and equipped with sophisticated cooling systems able to provide powerful cooling power with high response. The cooling system is based on (gaseous and liquid) nitrogen, so to make ReStoX functionalities totally independent from power failures. The stored xenon can be continuously purified thanks to a dedicated connection through a heat exchanger with the XENON1T purification system (which requires xenon in gaseous phase). As recovery system, ReStoX uses the simple principle of the communicating vases. ReStoX is kept at low pressure all the time (below a barg). In case of need of a recovery (voluntary or emergency-triggered) from the cryostat, the pressure in the cryostat (usually bigger than 2 barg) is enough to push liquid xenon through a dedicated recovery line in connection with ReStoX. Because of the siphon principle, all liquid xenon will be transferred in a very natural way once the transfer starts. Then ReStoX will be able to recover also most of the remaining gaseous xenon by subcooling the stored xenon and thanks to a direct gas-gas connection with the cryostat.

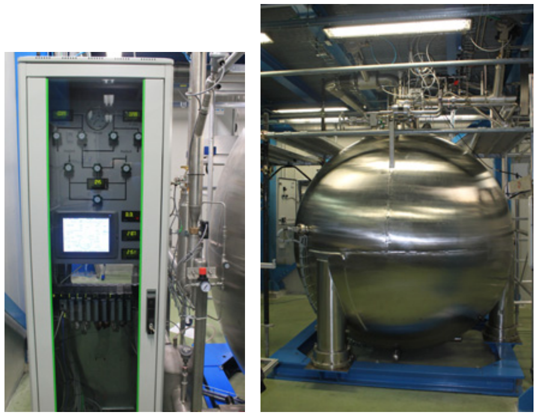

Figure 2. On the right the ReStoX stainless steel sphere to store and recovery the xenon which was put on site on August 2014. On the left it is shown its slow control system (PLC and touchscreen) enclosed in a 19-inches rack.

Figure 3. On the left the stainless steel water tank with a height of ∼10 m and a diameter of 9.6 m. It is equipped to work as Cherenkov detector; the implemented veto will reject the muon background. On the right the attractive service building with its 3 floors.

2.1 Expected background and sensitivity

In order to get the best sensitivity, a low-rate counting experiment like XENON1T has to reduce the sources of background to approximately zero level. One of this source is represented by cosmic muons which produce secondary neutrons as they interact near the detector, thus producing nuclear recoil background. Even if the muon flux is highly reduced at the site (LNGS stays under 3600 m.w.e.), the not much muon induced neutrons can be still nuisance in the signal region. To avoid this, the TPC and its cryostat will be immersed in 700 t of pure water contained in a stainless steel tank. The tank is equipped with an active muon veto with 84 PMTs, allowing a 99% efficiency in tagging crossing muons and 74% efficiency for showering events. The expected total background is expected to be around 0.01 event per year [7]. The water tank was completed in fall of 2013 and it is shown on the left of Fig. 3; on the right of the same picture it is shown the XENON1T service building which was completed at the beginning of 2014.

Other background from within the underground walls will be also effectively reduced by the passive shielding provided by the water tank and the outer volume of xenon.

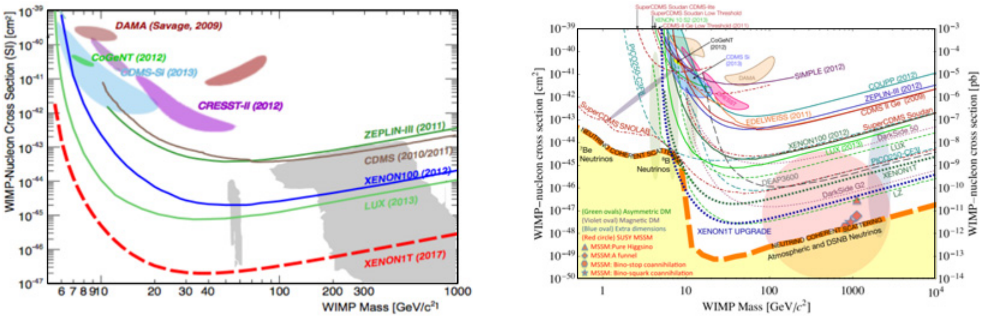

Figure 4. On the left the projected spin-independent WIMP-nucleon cross section sensitivity of XENON1T (red dashed line) after two years of operation, compared with current experimental results (adapted from [10]). On the right the projected sensitivity of the XENON1T Upgrade (blue dotted line) compared with present and future direct dark matter experiments (adapted from [11]).

The use of radio-pure raw material to build the different detector components is essential in order to reduce background contamination, and for this purpose several screening campaigns were performed and others are ongoing. The choices of the stainless steel used to build the cryostat and of the part of material which will be used for the TPC are indeed outcomes of these screening campaigns. The two arrays of low-background PMTs, 127 on top and 121 on bottom of the TPC, are 3-inches R11410-21 manufactured by Hamamatsu Photonics K.K., characterized by a high Q.E. = 32.5% @ 178 nm and a gain of a factor 3×10^6. The contamination measurements was performed with different techniques, such as high purity germanium screening, mass spectrometry and neutron activation [8, 9]. The estimate of the total background from the different material contamination results then to be about 0.25 events/year.

The xenon is commercially obtained from the fractional distillation of the air, thus containing krypton contamination at a certain level. This is then a source of intrinsic background since a factor of $\sim 2 \times 10^{-11}$ of krypton occurs as the unstable isotope ^{85}Kr, a β emitter. The only way to reduce such krypton impurities is via distillation. So, before to start the physical run all the xenon will pass once in a krypton distillation column with the aim to reduce the levels of contamination to below the ppt level (0.1×10^{-12} Kr/Xe). To filter the xenon from the electronegative impurities like O_2, N_2, and H_2O, it will keep circulating in a purification system with getters. The estimate of this intrinsic background results in about 0.15 events/year.

The solar neutrino and the double beta decay of ^{136}Xe (about 10% of natural xenon) represent the two sources of irreducible background. The contribution of both of these backgrounds is estimate to about 0.09 events/year, making the total background prediction from all the sources so far discussed to about 0.5 events/year.

The different background estimates so far discussed come from the assumption that the XENON1T analysis will have similar acceptance and background rejection with respect to the XENON100 analysis. Under this assumption, the increase in total mass (to 3 tonnes), coupled with the reduction in background levels to 6×10^{-5} events/kg/day/keVee, allows for two order of magnitude improvement in sensitivity with respect to XENON100. The analysis is based on a one ton fiducial volume, 5–50 keV search window for nuclear recoils, rejection of 99.5% of electronic recoil events, and acceptance of 50% of nuclear recoil events. The estimate sensitivity to the spin-independent WIMP-nucleon cross section is shown on the left of Fig. 4.

The XENON1T experiment has been designed to allow for the rapid deployment of a new detector with a total xenon mass of up to seven tonnes, named as XENON1T Upgrade. This new detector can be realized using the same cryogenic and purification infrastructure and will be housed in the existing XENON1T water tank (see next section for details).

3. XENON1T upgrade

Once completed in 2015, XENON1T will be proved to be the most sensitive worldwide dark matter experiments. The XENON1T will reach its design sensitivity after two years of stable operation.

The XENON1T Upgrade project will contain about 7 tons of xenon with an achievable goal of 20 ton-years of exposure. This will allow a sensitivity down to $3 \times 10^{-48}\,\text{cm}^2$ in the spin-independent WIMP-nucleon cross section.

The construction of the detector upgrade is foreseen to start as early as 2018, and will run in parallel with the operation of XENON1T. Most of the detector installation have been conceived to be reused to host a larger volume TPC without modifications: only a new inner vessel of the cryostat, which will fit with the existing outer cryostat, and the TPC itself will be needed. Signal and high voltage cables for the new PMTs 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, as well as the cryogenic and purification systems for the operation of the new detector. However the main cost of the experiment will be procurement of additional xenon and PMTs.

The projected sensitivity of the XENON1T Upgrade is shown on the right of Fig. 4.

4. Conclusion

We have presented the status of the XENON1T experiment which is under construction at the Laboratori Nazionali del Gran Sasso in Italy. It is currently under commissioning and the first results are foreseen for later 2015. With XENON1T and the planned upgrade, the XENON Collaboration plans to remain at the forefront of the exciting and challenging field of dark matter direct detection.

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