Status of the XENON Project

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Abstract. Astronomical and cosmological observations indicate that a large amount of the energy content of the Universe is made of dark matter. The most promising dark matter candidates are the so-called Weakly Interacting Massive Particles. The search for these particles is performed with various experimental approaches. The XENON Project, at the Gran Sasso National Laboratory, is devoted to the direct search of dark matter particles. It consists in operating a double-phase time projection chamber using ultra-pure liquid Xenon as both target and detection medium for dark matter particle interactions. The WIMPs can be indeed detected via their elastic scattering off Xenon nuclei.

The XENON100 detector with 160 kg of liquid Xenon has reached in 2012 the sensitivity of \(2 \times 10^{-45} \text{ cm}^2\) at 55 GeV/c\(^2\) and 90% confidence level on spin-independent elastic WIMP-nucleon scattering cross section. The next generation XENON1T detector, that will host 3.3 tonnes of ultra-pure liquid Xenon, is in its final stage of construction and will likely start taking data by the end of 2015. The detector is designed to increase the sensitivity by two orders of magnitude.

1. Introduction

Astrophysical and cosmological observations (such as the discrepancy between the expected and observed rotational curves for spiral galaxies, results from gravitation lensing measurements and on Cosmic Microwave Background anisotropy) indicate that a considerable amount of the energy content of the Universe is made of dark matter. Dark matter candidates, usually identified under the generic name of Weakly Interacting Massive Particles (WIMPs), naturally arise in many theories beyond the Standard Model, such as Supersymmetry, Universal Extra Dimensions, or little Higgs models. WIMPs are non baryonic dark matter candidates, they are non relativistic (i.e. cold), stable (created in thermal equilibrium in the early Universe) and interact with standard particles via a force similar in strength to the weak nuclear force.

The XENON dark matter program is devoted to the direct detection of dark matter in the form of WIMPs. The XENON detector is based on a time projection chamber (TPC) which uses liquid xenon (LXe) as both WIMP target and detection medium, with simultaneous measurement of the ionization and scintillation signals produced by particle interactions in the active volume.

After the successful results obtained by the XENON10 and XENON100 detectors, the XENON collaboration is now focused on the new XENON1T detector in final construction phase at the Laboratori Nazionali del Gran Sasso (LNGS); the increase in target mass and the careful selection of radiopure materials and the use of a water shield, acting also as active muon veto, will allow to reach a sensitivity to the spin independent (SI) WIMP-nucleon interaction cross section of \(2 \times 10^{-47} \text{ cm}^2\) or better.
2. The XENON detectors working principles

The detectors of the XENON program are based on similar designs and detection principles (see [1]). The innermost part of the detector is a time projection chamber containing xenon in liquid (LXe) and gaseous (GXe) phase. A stainless steel double-wall structure hosts the TPC and keeps it insulated from the environment temperature. As shown in figure 1 a particle that interacts with the LXe produces a prompt scintillation signal (S1) through excitation, and ionization electrons. The electrons can recombine, participating to the S1 signal, and/or can be drifted by an appropriate electric field towards the liquid-gas interface where they are extracted into the GXe producing the secondary scintillation signal (S2). Two arrays of photomultipliers (PMTs), one on the top and one on the bottom of the TPC, are used to detect the S1 and S2 signals.

![Diagram of XENON detectors](image)

**Figure 1.** Left: working principle of the XENON liquid/gas dual-phase TPC. Right: sketch of the waveforms of nuclear recoils (WIMPs and neutrons) and electronic recoils ($\gamma$ and $\beta$ background), showing the different ratio of the charge (S2) and light (S1) signals for the two types of events [1].

From the hit pattern of the top PMTs it is possible to reconstruct the x-y coordinate of the interaction vertex with an uncertainty of about 3 mm, while from the delay between S1 and S2 it is possible to infer the z coordinate of the event (uncertainty of about 0.3 mm); hence, it is possible to have a 3D vertex reconstruction of the scattering events. That capability is crucial since it allows to select an inner region of the LXe, usually called fiducial volume. Thanks to the self-shielding properties of the Xenon, the fiducial volume is characterized by a very low background level, a mandatory requirement for an experiment that looks for very rare events such as dark matter interactions. The ratio, S2/S1, is different for electric recoil (ER) and nuclear recoil (NR), which provide background discrimination in addition to the fiducialization. The XENON collaboration nowadays consists of 21 institutions and about 120 collaborators from all over the world. The XENON detectors have been operating at the LNGS in Italy at an average depth of 3600 m w.e. since 2006, starting with XENON10 and continuing with XENON100. The ton-scale next stage of the project, XENON1T, is under final construction phase, and is expected to finish commissioning by the first months of 2016.
3. Results from the XENON100
In 2012 the XENON collaboration released the results of a 225 live-days run with the XENON100 detector: no dark matter signal was found thus, only upper limits on the WIMP-nucleon spin independent interaction have been set, with a minimum of the cross section at $2.0 \times 10^{-45}$ cm$^2$ for WIMP mass of $m_\chi = 55$ GeV/c$^2$ (90% C.L.) (figure 2 left) [2]. Since natural xenon contains two nonzero spin isotopes ($^{129}$Xe, spin-1/2 and 26.4% of abundance, and $^{131}$Xe, spin-3/2 and 21.1% of abundance) it is possible to study spin dependent (SD) WIMP-nucleon cross section; using the 225 live-days dataset it was possible to set the most stringent limits on the SD WIMP-nucleon cross section: XENON100 excludes WIMP-neutron cross section as low as $3.5 \times 10^{-40}$ cm$^2$ for WIMP mass of 45 GeV/c$^2$ with 90% C.L. (Figure 2 right) [3].

Figure 2. Results on WIMP-nucleon scattering from XENON100. Left: SI WIMP-nucleon expected cross section limit shown by the green/yellow band (1$\sigma$/2$\sigma$) and the resulting exclusion limit (90% C.L.) in blue. For comparison, other experimental results are also shown, together with the regions (1$\sigma$/2$\sigma$) preferred by supersymmetric (CMSSM) models (updated from [2]). Right: WIMP SD cross section on neutrons; the 1$\sigma$/2$\sigma$ uncertainty on the expected sensitivity of this run is show as a green (yellow) band [3].

The 225 live-days data have been used to investigate the axions and axion like particles (ALPs) hypotheses that are well motivated cold dark matter candidates which interact predominantly with atomic electrons. For that reason XENON100 electron recoils (ER) events instead of nuclear recoils (NR) have been analyzed. Also in this case, the analysis shows compatibility with the background-only hypothesis and thus upper limits have been set. In particular, XENON100 set the most stringent limit on the axion coupling to electrons excluding values above $7.71 \times 10^{-12}$ (90% C.L.) and it also set the strongest upper limits on ALPs-electron coupling, in the $5 - 10$ keV/c$^2$ mass range, excluding couplings above $1 \times 10^{-12}$ (90% C.L.) [4]. The XENON100 data have been used to perform analysis aiming at reconciling the apparent tension between XENON100 and other experiments with the possible dark matter signal observed by the DAMA/LIBRA collaboration. In particular one study uses data from the XENON100 experiment to search for dark matter interacting with electrons finding no evidence for a signal above the low background. These results provide the possibility to exclude dark matter models that would induce electronic recoils: leptophilic models as explanation for the long-standing DAMA/LIBRA signal, such as couplings to electrons through axial-vector interactions at a 4.4 $\sigma$ confidence level, mirror dark matter at 3.6 $\sigma$, and luminous dark matter at 4.6 $\sigma$ [5].
The other analysis search for variations of the electronic recoil event rate in the (2-6) keV energy range recorded between February 2011 and March 2012. The results suggest no statistically significant modulation in the data. In the same analysis the DAMA/LIBRA annual modulation interpreted as a dark matter signature with axial-vector coupling of WIMPs to electrons is excluded at 4.8 $\sigma$ [6].

4. Design and status of the XENON1T

The new phase of the XENON program is the XENON1T experiment that will be the first ton scale liquid xenon detector. The construction of XENON1T started in 2013 in the Hall B of the LNGS in Italy and it is currently under commissioning phase; figure 3 shows both a drawing (left) of the XENON1T and a picture of the experimental area (right).

![Figure 3. The XENON1T experiment: drawing (left) and picture (right) of the experimental area.](image)

The experience acquired with the previous detectors helped in the design and construction of the XENON1T experiment; anyway the operation of a ton scale detector poses some new technical challenges. Indeed special custom storage, cryogenic, purification systems were designed and constructed. The goal of the experiment is to improve the sensitivity on SI cross section by two order of magnitude; to do this the increase on target mass is connected to extremely low radioactive background requirements. Detector materials were carefully chosen, and water Cherenkov muon veto and Kr distillation column were built.

The XENON1T detector will be hosted (fig. 3 left) inside a Water Tank (WT) acting as a shield against low energy gammas and neutrons. The WT, about 10 m height and 10 m diameter, is also equipped with 84 8-inch, high quantum efficiency PMTs to reveal Cherenkov light emitted by cosmic muons entering the water volume. So the WT will operate as an active muon veto able to reject neutron with muon in the water tank at more than 99.5% efficiency and reject neutron with muon outside the water tank at more than 70% efficiency resulting in a muon induced neutron estimated background of less than 0.01/year/ton [7].

Another background that needs to be reduced is the internal $\beta$-background from $^{85}$Kr. The XENON1T requires Kr concentration less than 0.2 parts-per-trillion. Since commercially available Xe contains Kr of about 5 parts-per-billion a cryogenic distillation column was designed and built to reduce Kr contamination: the column [8] uses the difference in condensation temperatures between Kr and Xe to remove Kr from Xe and has high throughput of about 3 kg/hr and capability of Kr concentration reduction factor of about $10^5$.

A custom storage system was designed and built (named RESTOX) capable to store about seven tons of Xe in both liquid and gaseous forms (and also to fast recuperate it): the detector can be filled directly with LXe. In case of emergency, LXe can be quickly recovered to the storage
Two redundant pulse tube refrigerator towers were designed, built and successfully tested to keep the detector cold in LXe temperature in a reliable way for long term operation [9]. For the long term operation, redundant compressors and water chillers were also installed. A $LN_2$ cooling system is foreseen in case of emergency.

In order to reduce at the ppb level electronegative impurities continuous high speed GXe circulation system (about 100 standard litter per minute) two parallel purification circuits have been designed, built and validated. To remove the electronegative impurities, commercial high-flow hot getters were installed.

The electric field inside the TPC, 96 cm height and 96 cm diameter (for a total of about two tons of LXe target), will be supplied by a cathode at bottom of the TPC and a gate at a few mm below the liquid level. The drift electrons will be extracted by electric field supplied by the gate and anode a few mm above the liquid level, and accelerated in gaseous phase. Custom-made HV feedthrough for cathode was designed and successfully tested up to 100 kV in LXe.

248 3-inch PMTs (Hamamatsu R11410, quartz window, bialkali photocathode with average quantum efficiency of 35% at 178 nm) are installed at bottom and top of the TPC.

Finally a full Geant4-based XENON1T Monte Carlo simulation [10] has been developed, including radioactivities of all detector materials, and energy deposition. The XENON1T expected 90% confidence level SI WIMP-nucleon cross section upper limit will reach better than $2 \times 10^{-47} \text{ cm}^2$ at WIMP mass of 50 GeV/$c^2$ with 2 ton·year exposure. The XENON1T will exceed the current XENON100 and LUX limits in about two and five days.

References
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