Status of XENON at LNGS - Report to the SC

The XENON Collaboration

Spring 2019

1 The XENON Collaboration

The XENON collaboration currently consists of 158 members from 27 institutions.

2 XENON1T

2.1 Current Status

In October 2018 the new calibration source ^{37}Ar has been added to the XENON calibration system. This isotope decays into ^{37}Cl by electron capture with a half-life of 35 days, emitting two lines at 2.8 keV and 0.27 keV, thus providing point-like energy deposition in the liquid xenon (LXe) with low-energy mono-energetic lines. These calibration lines are the lowest so far used for LXe TPCs, and is thus of prime importance for XENONnT. A first calibration campaign has been performed in October and November 2018; the analysis of the data is ongoing and very promising, see Figure 1. In particular, we managed to effectively remove the source via cryogenic distillation.

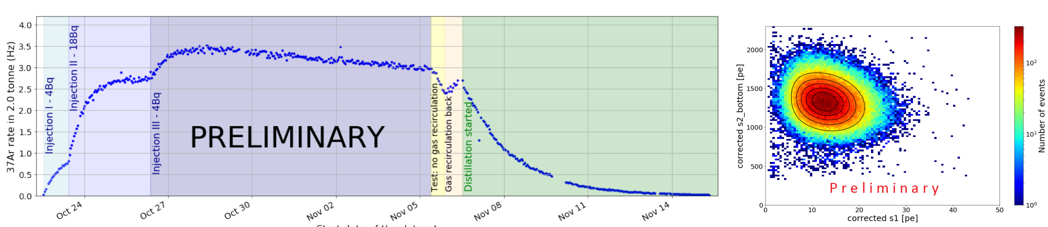

Figure 1: An ^{37}Ar calibration run was performed in fall 2018 to investigate the use of this low-energy source for XENONnT. **(left)** The isotope has been injected three times and was successfully removed via cryogenic distillation after data-taking. **(right)** The image shows the clearly visible 2.8 keV line in the charge-vs.-light parameter space.

Additional calibration runs have been acquired with a new ^{83m}Kr source as well as with the neutron generator. Data taking for XENON1T has been officially terminated on December 3rd,

2018. One week prior to the recuperation of the entire liquid xenon inventory into the ReStoX vessel a 'stress test' of the new XENONnT data acquisition system using the XENON1T PMTs as input channels was carried out. The test was successful and will considerably reduce the commissioning time of the final system.

2.2 Analysis

The analysis effort on medium-energy electronic recoils (ER) for the search of the two-neutrino double electron capture (2νECEC) has resulted in a publication accepted by Nature, *First observation of two-neutrino double electron capture in* ^{124}Xe *with XENON1T*. It reports the first observation of this second-order weak interaction process, with a half-life of $(1.8\pm0.5)\times10^{22}$ years (see Figure 2). This is the longest half-life ever measured directly. We note that this result is still under embargo and should be kept confidential.

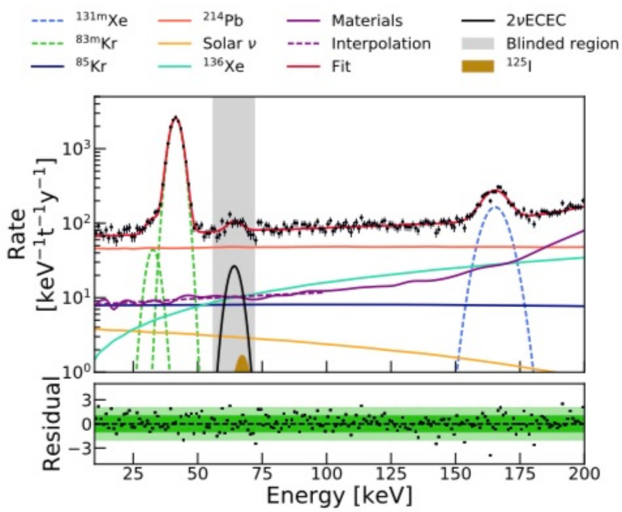

Figure 2: Measured background energy spectrum in the 1.5 t inner fiducial mass, showing the region where the 2νECEC electron capture signal is visible. The data in the grey band had been blinded.
This plot is still under embargo and must not be distributed.

The first analysis searching for interactions of WIMPs with virtual pions present in the nucleus as mediators of the nuclear force has been published by Physical Review Letters [3]. This study was performed in collaboration with theorists outside of the XENON collaboration.

Another manuscript has been recently accepted by Physical Review Letters, "Constraining the spin-dependent WIMP-nucleon cross sections with XENON1T". This publication reports on the most stringent constraint on the spin-dependent, WIMP-neutron cross section, with a minimum at a cross section of 6.3×10^{-42} cm^2 at 30 GeV/c^2 and 90% confidence level [2].

The manuscript "XENON1T Dark Matter Data Analysis: Signal & Background Models, and Statistical Inference" [1], which describes the details of our WIMP analysis, has been uploaded to the arXiv and submitted to Physical Review D.

An intense analysis campaign is still ongoing to maximize the scientific output from existing XENON1T data, exploring various science channels. Topics include annual modulation, solar axions, dark photons, axion-like particles, single electron recoil signals, search for the neutrinoless double beta decay of ^{136}Xe, inelastic SD scattering, etc. To increase the statistics, we are working on including Science Run 2 data (about 110 days, to be compared with the 278 days of Science

Run 1) to the data set. In addition, we are working on several technical papers describing relevant subsystems of XENON1T.

3 XENONnT

After the end of data taking and a 1-week test of the upgraded XENONnT data acquisition system using data acquired with XENON1T on December 3rd, 2018, the collaboration started the various operations for the decommissioning of the current TPC and the installation of the new one, as well as the systems upgrades foreseen for XENONnT.

Figure 3: Upgrades to the XENON infrastructure. **(Left:)** A *grey room* was installed in front of the Water Tank entrance to improve cleanliness. **(Right:)** The class ISO-6 clean room was moved from Lab2 to Hall di Montaggio and expanded by 50% in area.

On December 10th the water tank (WT) was emptied, a procedure that was completed in two days. The WT has been subsequently connected to fresh air ventilation to dry it completely. Immediately afterwards, we started to transfer the xenon to the storage system ReStoX, completely emptying the cryostat in four days. The WT has been opened in January and a careful inspection was carried out, revealing only minimal traces of oxidation. Preparations then began for the TPC decommissioning operations: a large gray room was installed in front of the WT entrance (see Fig. 3, left), the Muon Veto PMTs inside the WT were protected, a *catwalk* was set up to facilitate movements in and out of the WT avoiding the door step, and the work platform around the crystat was installed and extended to accomodate the new and improved cleanroom (see below).

In parallel, the new XENON above-ground area in the Hall di Montaggio was occupied by the collaboration. Due to delays beyond our control, the large XENON cleanroom, which had to be relocated from its old place in Lab2 and was extended to accomodate the larger XENONnT (see Fig. 3, right), was only ready to be used end of February 2019.

Cryostat. In February, a new class ISO-6 clean room has been assembled inside the water tank, encasing the cryostat (see Figure 4, left). The disassembly of the cryostat was started on March 4th. After the removal of the outer and inner vessels of the cryostat, the XENON1T TPC was inspected and no peculiarities were observed (see Fig. 4, right). While the PMTs from the TPC and other components to be re-used for XENONnT were recovered (e.g., the high voltage feedthrough), the TPC electrodes will be inspected more thoroughly using microscopes. The outer vessel including the top dome was shipped to Costruzioni Generali to modify it according to the XENONnT design, which requires a few smaller modifications on the top dome to support

Figure 4: **(Left:)** The outer XENONnT cryostat inside the newly installed class ISO-6 cleanroom inside the water tank. Its implementation is a major improvement in terms of cleanliness and background control compared to XENON1T. **(Right:)** The XENON1T TPC right after opening the cryostats and before its decommissioning to recover components (mainly the PMTs) for XENONnT.

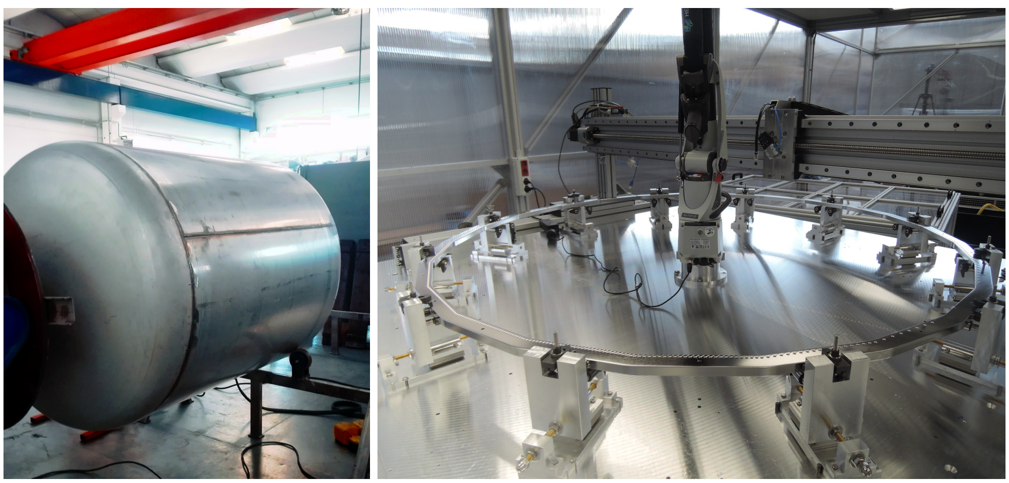

Figure 5: **(Left:)** The new XENONnT inner cryostat is under construction at Costruzioni Generali. It can accomodate more than 8 t of LXe **(Right:)** The XENONnT top screen electrode ready to be equipped with stainless steel wires of 216 μm diameter. The setup to measure the wire tension can also be seen.

the larger weight of the new experiment and a vertical extension of the cylindrical cryostat vessel. The inner vessel is currently being constructed at the company (see Fig.5, left).

TPC. The design of the TPC has been completed in September 2018. The field cage features 70 wire field shaping rings of 2 mm diameter and 64 XENON1T-like massive field shaping rings made from OFHC copper. This configuration was chosen based on extensive studies with finite element field simulations and aims at minimizing the charge up of the PTFE walls. The TPC electrodes are made from high-precision linear stainless steel wires of different diameters. A novel mechanism to fix the wires individually was developed and successfully tested using a real-scale mockup of the anode frame. The wires are currently being cleaned and installation of the wires on the frames is expected to start soon (see Fig. 5, right).

The procedures for the insertion of the PMTs, the assembly of the field cage, the insertion of the PTFE reflector walls and the overall assembly of the TPC have been finalized and approved during the technical meeting in January 22-23 at LNGS. All the cleaning and assembly steps will take place in the enlarged ISO-6 clean room which has been installed in the Hall di Montaggio (see Figure 3, right). The production of the TPC parts has started at companies and several collaboration institutes.

We have decided to commission the cryogenics system prior to the final phase of the TPC installation in order to verify our novel liquid xenon purification system (see also "Liquid Xenon Purification" further below). The test will also allow us to cool down the TPC electrodes in conditions reflecting true operations prior to their installation inside the TPC.

PMTs and Readout. A total of 494 Hamamatsu R11410-21 low-background PMTs are required to instrument the XENONnT TPC; 248 tubes were installed in XENON1T. The recuperation of those XENON1T PMTs to be re-used for XENONnT took place in early March. All PMTs are in a good condition and are currently being stored until their installation in the new TPC. All the new PMTs ordered from Hamamatsu have been delivered and were tested in various conditions (warm, cold, LXe).

The new voltage dividers (bases) for the PMTs are ready and are undergoing final testing. The LXe-side signal and high voltage cables will soon be soldered to the bases in preparation for assembly of the photosensor arrays. All air-side cables as well as all electronics crates, modules, and computers to read-out the TPC are either re-used from XENON1T or were ordered. The XENONnT data acquisition system will be based on the same "triggerless" paradigm as the one for XENON1T, but an optimization of the used data formats led to a tremendous increase in readout speed. The new system was successfully tested on XENON1T in late 2018.

ReStoX2. The ReStoX2 system has been tested, with several cooling cycles carried out in February. The system is considered ready to receive the xenon from the Rn distillation column (see below), however, we are waiting for the green light from the LNGS Safety Office before starting the filling operations.

Distillation of Xe for nT Presently the Kr distillation column contains about 5 kg of LXe and is ready for the distillation to be started. In total, more than 5 tons of xenon will be transferred from (∼100) bottles to ReStoX2. The bottle rack has been upgraded (with respect to XENON1T) to host two independent sets of four bottles. The bottles will be analyzed with RGA and distilled in batches of four (at a process speed of 3 kg/h).

Liquid Xenon Purification. The design of the cryogenic liquid xenon purification system was finalized in January 2019. The fabrication of the system is ongoing at Costruzioni Generali. Its delivery to LNGS is expected in mid-April, along with the vacuum-insulated lines connecting the system to the cryostat and other systems. The system consists of two insulated vessels for the two independent Barber-Nichols liquid pumps and two insulated vessels containing the filter material being tested on the LXePUR-Demonstrator set-up at Columbia University. The liquid xenon purity monitor to be used in the purification system has already been built and tested at the University of Tokyo. It will be delivered to LNGS at the end of March. The integration of the purification system with other XENONnT systems and Slow-Control is planned for the end of April. A commissioning test of the cryogenic purification system is currently being planned for the June-July period, while the TPC is being assembled above ground.

Radon distillation column. The new radon distillation column consists of four key parts, namely the top condenser, reboiler, package tube and compressor. The top condenser and reboiler are custom-made heat exchangers developed in Muenster. The smaller top condenser was built and tested in Muenster with liquid nitrogen as coolant and xenon as process gas. We successfully reached a xenon liquefaction rate of 115 slpm, which fulfills the design goal of 100 slpm. Based on the results, the larger heat exchanger at the bottom (reboiler), is being designed and under construction. The package material that provides a large surface for a better separation was sent to MPIK Heidelberg for radon emanation measurements and to test different cleaning methods. A four-cylinder magnetically-coupled piston pump will be used as a radon-free compressor with flows up to 200 slpm. Its design is based on the single-cylinder magnet pump [4] that was successfully operated 24/7 as XENON1T circulation pump over the course of seven month in the second half of 2018. All parts for the new pump are ordered and mostly delivered. The construction of several parts started already. The radon distillation system is expected to arrive at LNGS by Fall/Winter 2019 and will be installed at the top floor of the XENON service building next to the cryogenic system.

Neutron Veto. The design of the neutron veto has been finalized in September 2018. We chose to add 3.4 t of Gd-sulphate-octahydrate to the muon veto water, which will correspond to a concentration of 0.2 % of Gd in mass. An additional 120 PMTs will be placed in the water surrounding the cryostat to detect the Cerenkov photons emitted after neutron capture. Moreover, a high-reflectivity, 1.5 mm thick, ePTFE foil will optically isolate the region of the neutron veto (see fig. 6) to enhance the light collection efficiency, and so the neutron tagging efficiency. According to Monte Carlo studies, a ten-fold coincidence among the n-veto PMTs will correspond to a neutron tagging efficiency of about 85%, allowing at the same time to keep the background rate induced by the PMT radioactivity to a sustainable level. The PMTs have been ordered and will arrive at LNGS in batches starting March 25th, where they will be tested for dark rate, gain, and single photo-electron response by June. The installation of the neutron veto structure, PMTs and reflector is foreseen for September. Its commissioning will start right after the first filling with standard water, as in this case the neutron tagging efficiency is still of about 65%, so we can start the first calibration runs with neutron sources.

3.1 Summary

The XENON1T decommissioning is completed, and analysis work is ongoing. One manuscript has been accepted by Nature, one by Physical Review Letters and another one has been submitted to Physical Review D. Additional papers are expected to be published in the next months.

The construction of the new systems for XENONnT is ongoing at various institutions and at companies. A compressed version of the schedule is presented in Figure 7. The goal is to start commissioning of XENONnT cryogenics and purification in liquid phase as soon as the new LXePUR system and cryostat are installed. This step will be done without the TPC (but with the TPC electrodes to test them in their final cryogenic environment). Establishing the fast and effective purification of the multi-tons of LXe for XENONnT is our first milestone. We expect to have the TPC installed in the cryostat by August. We will subsequently remove the cleanroom from the water tank to enable the installation of the neutron veto structure prior to filling water in the muon veto/neutron veto systems to start commissioning the new TPC. We cannot test the new detector's performance without water shielding. We expect to be able to add Gd to the water by January 2020 in order to start the full physics program with XENONnT.

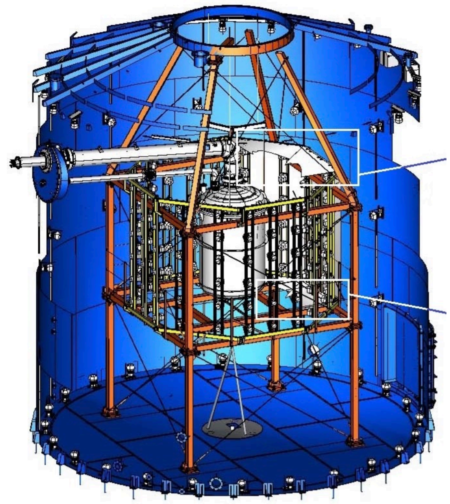

Figure 6: The neutron veto system: in yellow the support structure for PMTs and ePTFE reflector foil.

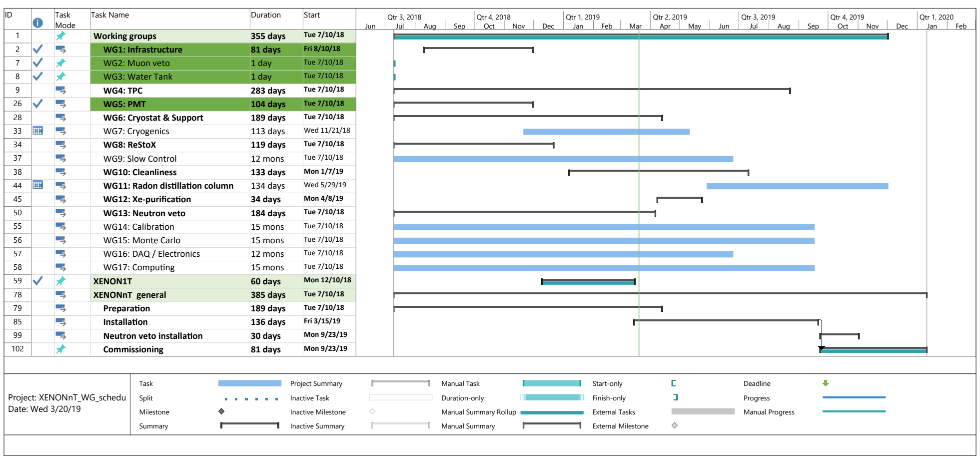

Figure 7: Updated schedule for the XENONnT project.

References

[1] E. Aprile et al. (XENON1T), *XENON1T Dark Matter Data Analysis: Signal & Background Models, and Statistical Inference*, arXiv: 1902.11297.

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