

# The XENON100 Dark Matter Experiment at LNGS: Status and Sensitivity

**Elena Aprile (on behalf of the XENON Collaboration)**

Columbia University, Physics Department, New York, NY, USA

E-mail: [age@astro.columbia.edu](mailto:age@astro.columbia.edu)

**Abstract.** The XENON100 experiment aims at the direct detection of cold dark matter particles via their collisions with xenon nuclei. The detector is a two-phase xenon time projection chamber, with an active target mass of 65 kg, shielded by 105 kg of liquid xenon as scintillator veto. Additional passive shielding surrounds the target to reduce the gamma and neutron induced background. The experiment is located underground in the Gran Sasso National Laboratory (LNGS) and is in the final stage of commissioning. I will summarize the status and sensitivity reach of the experiment, as well as the current plan for an upgrade.

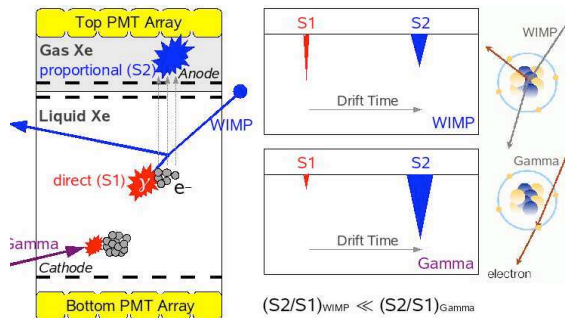
## 1. Introduction

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, 3]. Weakly Interactive Massive Particles (WIMPs) predicted by Supersymmetric theories (SUSY), models with extra dimensions and little Higgs models [4, 5, 6, 7] are favorite CDM candidates. Three different approaches are being pursued for WIMP detection: direct production of WIMPs in the highest energy particle collisions expected at the the Large Hadron Collider; indirect detection of WIMP annihilation signals from the center of the Sun or from the center of the galaxy, and direct detection of nuclear recoils produced by WIMPs scattering off normal matter.

The XENON project is one of several direct detection experiments worldwide, using a noble liquid as target and detector medium. After the successful results of the first 10 kg scale liquid xenon (LXe) detector XENON10 [8, 9], the collaboration has designed and built a second-generation detector, with the goal of significantly improving the sensitivity by lowering the background and increasing the target mass. Like XENON10, the new detector is a two-phase time projection chamber (TPC) with about a factor of 10 more target mass and about a factor of 100 less radioactive background. The sensitivity reach of the XENON100 experiment is a factor of 50 better than that of XENON10.

## 2. Detector Concept

The XENON100 detector is a double-phase (liquid-gas) time projection chamber (TPC). A particle interacting with the target generates scintillation light and ionization electrons (Figure 1). The primary light (S1) is detected immediately by the two photomultiplier (PMT) arrays above and below the target. An electric field ( $\sim 1$  kV/cm) across the TPC drifts the free ionization electrons upwards, where they are extracted into the gas phase by a strong extraction



**Figure 1.** Principle of a two-phase liquid xenon TPC. A particle generates primary scintillation light (S1) and ionization electrons. These are drifted upwards by an electric field and detected via secondary scintillation light in the gas phase (S2). The S2 hit pattern ( $xy$ ) and the drift time ( $z$ ) give the three-dimensional information on the position of events. Additionally, the ratio  $S2/S1$  allows event discrimination between nuclear recoils (WIMPs, neutrons) and electron recoils ( $\gamma$ ,  $\beta$ ).

field. In the gas phase, the electrons generate very localized secondary scintillation light (S2), that can be used to determine the  $xy$ -position of the interaction point. Since the  $z$ -position is known from the drift time, the event positions can be fully reconstructed and used to fiducialize the target volume in order to drastically reduce the radioactive background from external sources.

The high ionization density of nuclear recoils in liquid xenon leads to larger S1 and smaller S2 signals compared to electron recoils. The simultaneous measurement of charge and light provides a powerful discrimination between signal (nuclear recoils) and background events (electron recoils) via the ratio  $S2/S1$ . A discrimination of 99.5-99.9% was achieved in XENON10.

### 3. Experimental Setups

In XENON100, the LXe target volume of 65 kg (30 cm drift height and 30 cm diameter), is surrounded by 105 kg of LXe as active scintillator, for additional background rejection. PTFE is used as an effective UV light reflector in order to optically isolate the target from the surrounding LXe veto. A set of 40 field shaping rings and their resistive divider chain are mounted on the panels and create a homogenous drift field.

The light readout is based on  $1'' \times 1''$  Hamamatsu R8520-06-Al low-radioactive PMTs with quantum efficiencies up to  $\sim 35\%$ . 98 PMTs in the top array are arranged to improve position reconstruction, 80 PMTs on the bottom to optimize the light collection, and 64 PMTs in the LXe veto to give another factor of 4 in background reduction.

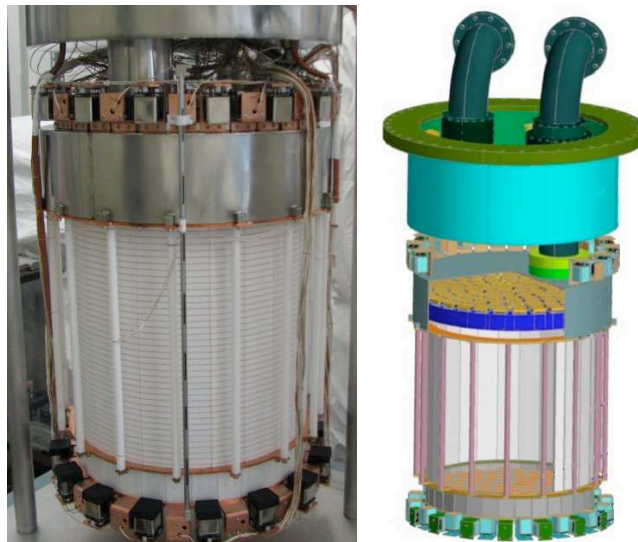
An Iwatani PC150 Pulse Tube Refrigerator (PTR) is used to liquefy xenon (170 W cooling power) and to keep the detector at the operating temperature of  $-100^\circ\text{C}$ . The refrigerator provides excellent stability of operation, with temperature variations below  $0.1^\circ\text{C}$  and pressure changes of less than 1%. In order to minimize the radioactive background in the detector, the cryogenic system is located outside the passive shield. This shield consists of 5 cm copper, 30 cm polyethylene and 20 cm lead. The cryostat and detector production was completed in early 2008 and the detector was installed underground at LNGS in Spring 2008. A picture of the XENON100 detector in front of its shield and the schematic view of the inner TPC are shown in Figure 2 and Figure 3, respectively.

#### 3.1. XENON Purification System

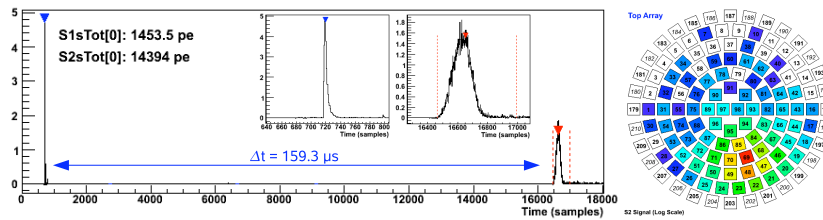
Successful operation of the xenon TPC requires long VUV light attenuation length and effective charge drift (long electron lifetime in liquid xenon). We are using a purification system based on continuous xenon gas circulation with purification through a high temperature metal getter (SAES) to reduce the impurities (water, oxygen etc.) in commercially available xenon to a level below 1 part per billion (ppb)  $\text{O}_2$  equivalent.



**Figure 2.** XENON100 after cleaning the cryostat and the shield cavity from dust, grease, stains, etc. right before closing the shield. The circular copper pipe around the detector is used for the insertion of calibration sources from outside the shield. The Pb brick visible in the front is necessary to block gamma rays from the AmBe source during a neutron calibration.



**Figure 3.** The XENON100 TPC. Left: Photo showing the PTFE panels as well as the veto PMTs on the top and bottom. Right: Drawing of the structure to show the location of the inner top and bottom PMT arrays.



**Figure 4.** Example of a XENON100 event with almost maximum drift time. The interaction happened close to the cathode. The insets show the enlarged S1 and the S2 pulses. The narrow pulse at 720 is the prompt S1 scintillation light, the broader peak at 16600 is the charge signal (S2). The  $xy$  position of the event can be reconstructed using the hit pattern of the S2 signal on the top PMT array.

Xenon can be purified from most radioactive impurities, except  $^{85}\text{Kr}$ . Krypton is present in commercial xenon gas at the few parts per million (ppm) level. The beta decay of  $^{85}\text{Kr}$  ( $E_{max} = 687$  keV,  $T_{1/2} = 10.6$  yr) is a significant source of background for any xenon based dark matter search experiment. In order to reduce the  $^{85}\text{Kr}$  level to below 50 parts per trillion (ppt) as required by the XENON100 sensitivity goal, we have installed and tested underground a cryogenic distillation column made by Taiyo-Nippon Sanso. The xenon has been purified with this system and data indicates a satisfactory reduction of  $^{85}\text{Kr}$ .

### 3.2. Readout Electronics and Data Acquisition

The XENON100 data acquisition system (DAQ) is used to generate a trigger signal for the TPC, digitize the waveforms of the 242 PMTs, and store this data. The PMT signals are first amplified by a factor of 10 (Phillips 776 amplifiers) and then digitized by CAEN V1724 Flash ADCs with a sampling rate of 100 MHz. A typical XENON100 waveform from a  $^{137}\text{Cs}$  calibration is shown in figure 4. The DAQ system is fully operational and used continuously to characterize the detector. Detector calibration is performed with several gamma sources, and the PMTs single photoelectron response is measured regularly with blue LEDs.

Apart from general performance tests, the first phase after installation was devoted to characterize the detector with S1 signals. The measured S1-background agrees with the MC simulation, suggesting that the envisaged background reduction by two order of magnitude was achieved. After some unexpected delays due to a leak in the cryostat seal, which lead to a limited LXe purity, we started to operate in dual-phase mode early 2009 and are now characterizing the fully operational detector with gamma sources.

## 4. Background

### 4.1. Materials Screening

To reduce the radioactivity from the detector and the shielding materials in order to improve the sensitivity of the experiment, radioactivity screening was performed with a high purity germanium spectrometer at LNGS. The radioactivity of all the components has been measured and is used as input for detailed Monte-Carlo simulations of the  $\gamma$  and neutron background of the experiment. The radioactive contaminations in a selection of materials screened is shown in Table 1.

**Table 1.** Results from some of the materials screened for radioactivity with high purity germanium spectrometers.

| Sample                | Unit      | $^{232}\text{Th}$ | $^{238}\text{U}$ | $^{40}\text{K}$ | $^{60}\text{Co}$ |
|-----------------------|-----------|-------------------|------------------|-----------------|------------------|
| Innermost Pb (shield) | [mBq/kg]  | <0.55             | <0.66            | <1.46           | <0.11            |
| Outermost Pb (shield) | [mBq/kg]  | <0.43             | <0.92            | $<14 \pm 36$    | <0.12            |
| Polyethylene (shield) | [mBq/kg]  | <0.094            | $<0.23 \pm 0.05$ | $<0.7 \pm 0.4$  | N.A              |
| Stainless Steel       | [mBq/kg]  | <1.9              | <1               | $8.5 \pm 0.9$   | $10.5 \pm 4.2$   |
| PTFE                  | [mBq/kg]  | <0.16             | <0.31            | <2.25           | <0.11            |
| 22 QE PMTs            | [mBq/PMT] | $0.18 \pm 0.06$   | <0.24            | $11 \pm 2$      | $0.6 \pm 0.1$    |

#### 4.2. Nuclear Recoil Background

Spontaneous fission and ( $\alpha$ , n) reactions in the detector, shielding materials, and surrounding concrete/rock are the major contributions to the nuclear recoil background events (neutron scattering). Using neutron yields and energy spectra calculated with a modified SOURCES4A code [10], we estimate the total neutron rate from PMT materials as 3.7 neutrons/year. For this neutron rate the expected number of single nuclear recoils in liquid xenon is  $1.4 \times 10^{-7}$  events/kg/day/keV (dru = differential rate unit) at 10 keVr.

The muon flux at the 3700 mwe (meter water equivalent) Gran Sasso depth is 12 muons/m<sup>2</sup>/day. Muons will produce neutrons in the lead and polyethylene of the shield due to electromagnetic and hadronic showers and through direct spallation. High energy muons interacting in the rock can produce highly penetrating neutrons with energies up to a few GeV. The total expected neutron background in XENON100 is  $1.3 \times 10^{-5}$  dru and thus well below the expected WIMP rate of  $2 \times 10^{-4}$  dru for a cross section of  $9 \times 10^{-45}$  cm<sup>2</sup>.

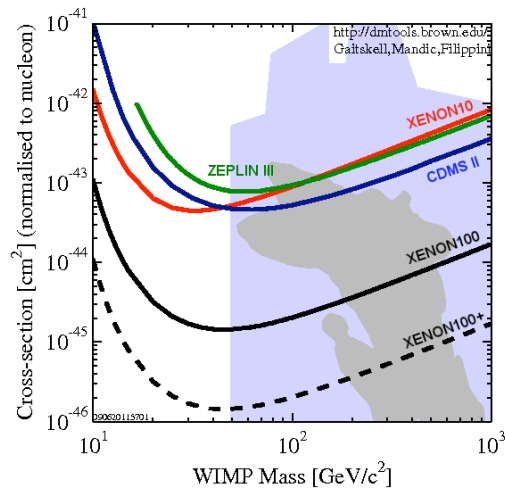
#### 4.3. Electron Recoil Background

Gammas from the decay chains of the radioactive contaminants in the detector materials (mostly  $^{238}\text{U}$ ,  $^{232}\text{Th}$ ,  $^{40}\text{K}$ ,  $^{60}\text{Co}$ ) dominate the electron recoil background. The background rate was estimated using measured detector material activities listed in Table 1 as input parameters for GEANT4 [11] Monte Carlo simulations. The activity of the PMTs is the major contributor to the current XENON100 electron recoil background. The total electron recoil background in XENON100 is  $6 \times 10^{-3}$  dru. After 99% electron recoil rejection we obtain a conservative background rate of  $6 \times 10^{-5}$  dru.

To summarize, the expected rate of single scattering electron recoil signals is  $(24.05 \pm 0.17) \times 10^{-3}$  events/kg/day/keV and  $(9.07 \pm 0.14) \times 10^{-3}$  events/kg/day/keV for 50 kg and 30 kg fiducial mass, respectively. The total neutron induced single nuclear recoil rates are 1.62 n/year and 0.60 n/year for 50 and 30 kg fiducial mass, respectively.

### 5. XENON100 Sensitivity

A WIMP search with the current XENON100 will be first performed in a 50 kg fiducial volume with 40 live-days of exposure, to reach a sensitivity for a spin-independent WIMP cross section of  $\sigma \sim 6 \times 10^{-45}$  cm<sup>2</sup> for WIMPs with a mass of 100 GeV/c<sup>2</sup>. An improvement by a factor of three ( $\sigma \sim 2 \times 10^{-45}$  cm<sup>2</sup>) can be achieved after 200 days of data taking and a 30 kg fiducial volume, to remain background free. The expected sensitivity of XENON100, compared with the current limits, is shown in Figure 5.



**Figure 5.** Exclusion plots for spin independent WIMP-nucleon interactions. The current limits are the curves around  $10^{-43}$   $\text{cm}^2$ , given by XENON10 (red, [8]), CDMS II (blue, [13]), and ZEPLIN III (green, [12]). The projected sensitivity for XENON100 is one order of magnitude lower (black) and even better when upgraded to XENON100+. The shaded regions are theoretical expectations of some models.

## 6. XENON100+

The XENON100 gamma background is dominated by the PMTs and the PMT bases, followed by the polyethylene of the shield and the stainless steel of the cryostat. In order to achieve reduced background for the next step towards an even more enhanced sensitivity, the bottom PMT array will be replaced by 19 QUPIDs [14], novel photosensors with an extremely low intrinsic radioactivity, developed by UCLA and Hamamatsu for this experiment. Additionally, a copper cryostat and an improved shield with an active muon veto will be implemented. With such upgrade, a spin-independent WIMP-nucleon limit of  $2 \times 10^{-46}$   $\text{cm}^2$  could be achieved by 2012.

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