The XENON Dark Matter Search

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Abstract. The XENON100 experiment aims at detecting cold dark matter particles via their collisions with xenon nuclei in a two-phase time projection chamber filled with a total of 165 kg of ultra pure liquid xenon. The detector sensitive target mass is about 65 kg, surrounded by about 100 kg of active veto. The detector has been installed underground at the Gran Sasso National Laboratory (LNGS) since 2008 and after a successful calibration, dark matter data taking has started. The current status of the XENON100 as well as future plans for the upgrade are presented.

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]. 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 [4, 5, 6, 7]. Among the different WIMP detection approaches that are used in order to determine the characteristics of such particles are experiments at LHC looking for their appearance in collisions, high energy astroparticle physics experiments that are looking for WIMP annihilation signatures from the center of the Sun or from the center of the galaxy, and dark matter direct detection experiments that are looking for the scattering of WIMPs off target nuclei.

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 kg scale detector XENON10 [8, 9], the collaboration has designed and built a second-generation experiment exploiting the two-phase time projection chamber (TPC) technique based on liquid xenon (LXe). The XENON100 detector features an increase in mass by a factor of 10 and a reduction of the radioactive background level by a factor of 100, as shown by the first measured scientific data. XENON100 sensitivity reach is a factor of 50 better than that of XENON10.

2. Detector Concept
Liquid xenon is appealing as the target material for dark matter direct detection. It is a heavy (A = 131) and dense ($\rho \sim 3$ g/cm$^3$) medium and an efficient scintillator (80% of NaI). The high mass number provides excellent detection capabilities for the spin-independent WIMP-nucleon scattering ($\sigma \propto A^2$). The abundance of odd isotopes (about 50%) allows the detection of spin-dependent interactions ($\sigma \propto J(J+1)$). The high density and high Z provide self shielding against external gamma radiation. Xenon has no long lived isotopes and purification of krypton in xenon...
has been shown down to the level of a few ppt, which is an important advantage in the search for rare dark matter induced events.

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

The XENON100 detector is a two-phase (liquid-gas) time projection chamber (TPC). A particle interacting with the target generates electron ion pairs and excited xenon atoms, which produce scintillation light and free electrons in the medium (Figure 1). The primary light (S1) is detected immediately by the two photomultiplier (PMT) arrays above and below the target. An electric field (∼0.53 kV/cm) across the TPC drifts the free ionization electrons upwards, where they are extracted into the gas phase by an even stronger extraction field. In the gas phase, the electrons generate very localized proportional scintillation light (S2). The PMT hit pattern of the S2 signal can be used to determine the xy-position of the interaction point and since the z-position is known from the drift time, the event positions can be reconstructed in three dimensions. This allows to select an inner fiducial volume in our target which together with the self shielding capability of liquid xenon drastically reduces 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% has been achieved in both XENON10 and XENON100.

### 3. Experimental Setup

The XENON100 detector consists of 165 kg of liquid xenon divided in two concentric cylinders. The inner sensitive volume contains 65 kg of Xenon and is separated from the outer volume by a PTFE cage on the sides, a diving bell on the top and a PMT array in the bottom. Two electric field regions are created in this volume with one mesh in the bottom and three in the top, near the liquid gas interface. These electric fields allow electrons produced in interactions to drift in the main volume and be extracted to the gas where they produce proportional scintillation light. The PTFE cage acts as a reflector for the UV light from the liquid xenon and also accommodates a set of 40 field shaping rings and their resistive divider chain to improve the homogeneity of the field. The outer volume acts as an active veto reducing the amount of interactions in the inner volume and allowing to identify multiple scatter events. This in fact reduces the DAQ rate and the amount of data collected and improves our ability to reject gamma events as WIMP candidates.

The light readout is based on 1” × 1” Hamamatsu R8520-06-Al low-radioactive PMTs with quantum efficiencies up to ∼35%. 98 PMTs in the top array above the anode mesh are arranged
in a circular pattern to improve position reconstruction, while 80 PMTs on the bottom are arranged in a compact grid to optimize the light collection. 64 PMTs in the active veto allow to detect energy depositions as low as 100 keVee reducing the overall background by a factor 4.

The detector is surrounded by a passive shield consisting, from the inside to the outside of 5 cm copper, 20 cm polyethylene and 20 cm lead and 20 cm of water. All the systems associated with the cooling and the purification of the xenon are placed outside this shield in order to minimize the background level.

The cryostat and detector production was completed in early 2008 and the detector was installed underground at LNGS. An extensive calibration of the detector systems has been performed in 2009 and blind dark matter data taking started in January 2010. A picture and the schematic of the inner TPC are shown in Figure 2.

Figure 2. 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.

3.1. XENON Recirculation and Purification System

An Iwatani PC150 Pulse Tube Refrigerator (PTR) is used to liquefy xenon (170 W cooling power) and keep the detector at cryogenic temperature of -100°C. This provides excellent stability of operation, with temperature variations below 0.1°C and pressure changes of less than 1%.

Successful operation of the xenon TPC requires long VUV light attenuation 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 in commercially available xenon (water, oxygen etc.) to a level below 1 part per billion (ppb) O_2 equivalent.

While xenon has no long lived radio isotope, krypton is present at the ppm to ppb level in commercially available xenon. The isotope \(^{85}\text{Kr}\) (\(E_{\text{max}} = 687\) keV, \(T_{1/2} = 10.6\) yr) is present in krypton with a ratio \(^{85}\text{Kr}/\text{Kr}=10^{-11}\) and it represents a significant source of background for
any xenon based dark matter search experiment. In order to reduce the \(^{85}\)Kr level to \(\sim 100\) parts per trillion (ppt) as required by the XENON100 sensitivity goal, we have installed and used underground a cryogenic distillation column made by Taiyo-Nippon Sanso. The xenon has been purified with this system and we have measured with the method of delayed coincidences a \(^{85}\)Kr concentration of \(\sim 150\) ppt.

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 \(^{137}\)Cs calibration is shown in figure 3. 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.

![Figure 3](image-url)

**Figure 3.** Left: The XENON100 Data Acquisition System. Lower right: A typical electron recoil event in the XENON100 TPC. The S1 and S2 signals are separated by 85\(\mu\)s, yielding the Z position of the interaction point. Upper right: The X and Y positions of the interaction point can be reconstructed using the hit pattern of the S2 signals on the top PMT array.
4. Detector calibration

The XENON100 detector has been installed underground in LNGS since the middle of 2008, and has tested in a series of successful calibrations during this period. Monitoring of the detector performance has been done on a regular basis using $^{137}$Cs and blue LEDs to study the PMT gain, the light collection efficiency and the electron absorption. For dark matter detection one of the most important features of a two-phase liquid xenon TPC is the ability to distinguish between electronic and nuclear recoils. In order to characterize the electron recoil regions several calibrations with a $^{60}$Co source have been performed. A high energy veto has been used to acquire only the lower part of the spectrum $\leq 150$ keV.

To study the response to nuclear recoils, during December 2009 and for three days a calibration was performed with an AmBe neutron source. This allowed us to collect a large sample of elastic nuclear recoils, but also a rather homogeneous sample of 40 keV and 80 keV gamma-rays from inelastic scatterings which have been used to measure the energy resolution of the detector down to this energy. Figure 4 shows the measured electron and nuclear recoil bands. A discrimination between nuclear and electronic recoils better than 99% is found at all energies for a nuclear recoil acceptance of 50%.

\[\text{Figure 4. Discrimination between nuclear and electronic recoils using the ratio of charge and light. The red (blue) curve is the median of the nuclear (electronic) recoil band. Top: Electronic recoil band measured with a } ^{60}\text{Co gamma source. Bottom: Nuclear recoil band measured with an AmBe neutron source.}\]

5. XENON100 First Results

During the detector calibration period in 2009 some data were taken when no source was present and in ideal detector conditions. While this data were not originally blinded, we decided to perform a blind analysis on them by defining selection cuts only on the calibration data [11]. 11.2 days of data were analyzed with a fiducial volume of 40 kg. Only very basic cuts were defined, aiming to remove noisy events, events interacting in the gas or events with multiple interactions in the detector. After applying these cuts a total of 22 events were observed in the fiducial volume and the energy region preselected for the signal, corresponding to a background level of $\sim 7$ mdru, which is the lowest measured in a dark matter search up to date. None of the measured events lies in the nuclear recoil band, showing for the first time the successful background free operation of a liquefied noble gas TPC. Figure 5 shows the limit for spin independent dark matter parameter space established from this result, which already at this early stage of operation is comparable to the best exclusion limit to date.
Blind data acquisition started at the beginning of 2010 and to date more than 10 times the exposure used for this analysis has been collected.

6. XENON1T

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. The next step in the XENON dark matter project will be XENON1t, with a fiducial mass of \( \sim 1.1 \) ton. In order to achieve reduced background, PMT arrays will be replaced by QUPIDs [12], novel photosensors with an extremely low intrinsic radioactivity, developed by UCLA and Hamamatsu for this experiment. Additionally, a copper cryostat and 10 meter diameter water shield acting also as an active muon veto will be implemented. This detector will bring an improvement in the spin-independent WIMP-nucleon sensitivity of 2 orders of magnitude by 2015.

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