The XENON10 WIMP Search Experiment at the Gran Sasso Underground Laboratory

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Abstract.
XENON10 is a new direct dark matter detection experiment using liquid xenon as target for weakly interacting, massive particles (WIMPs). A two-phase (liquid/gas) time projection chamber with 15 kg fiducial mass has been installed in a low-background shield at the Gran Sasso Underground Laboratory in July 2006. After initial performance tests with various calibration sources, the science data run started on August 24, 2006. The detector has been running stably since then, and a full analysis of more than 75 live days of WIMP search data is now in progress. We present first results on gamma and neutron calibration runs, as well as a preliminary analysis of a subset of the WIMP search data.

1. Introduction
The goal of XENON [1] is to search for interactions of massive, cold dark matter particles in liquid xenon. The motivation of this search comes from our current understanding of the universe. Over the last ten years, a variety of cosmological observations, from the primordial abundance of light elements, to the study of large scale structure, to the observations of high redshift supernovae, to the detailed mapping of anisotropy of the cosmic microwave background, have led to the construction of a so-called concordance model of cosmology. In this model, the universe is made of $\sim$4\% baryons which constitute the ordinary matter, $\sim$23\% nonbaryonic dark matter and $\sim$73\% dark energy [2]. Understanding the nature of dark matter poses a significant challenge to astrophysics. The solution may involve new particles with masses and cross sections characteristic of the electroweak scale. Such Weakly Interactive Massive Particles (WIMPs), which would have been in thermal equilibrium with quarks and leptons in the hot early universe and decoupled when they were non-relativistic, represent a generic class of dark matter candidates [3, 4]. If WIMPs are the dark matter, their density in the Milky Way halo may allow them to be detected in laboratory experiments by looking for the nuclear recoils produced in elastic WIMP–nuclei collisions [5]. A WIMP with a typical mass between 10 GeV – 10 TeV will deposit a nuclear recoil energy below 100 keV in a terrestrial detector. The expected rates are determined by the WIMP-nucleus cross section and by their density and velocity distribution in the vicinity of the solar system [4]. Direct-detection experiments, in particular CDMS II [6, 7], CRESST [8], EDELWEISS [9], ZEPLIN II [10] and WARP [11], are beginning to significantly constrain the WIMP-nucleon scattering cross section and, for the first time, start

1 On behalf of the XENON collaboration
to probe the parameter space which is predicted by supersymmetric extensions to the Standard Model (recent reviews can be found in [12, 13, 14]).

While it is clear that cryogenic experiments such as CDMS are still leading the field, detectors based on liquid noble elements (Ar, Xe) are rapidly evolving and are already catching up in sensitivity. Liquid argon (LAr) and xenon (LXe) have excellent properties as dark matter targets. They are intrinsic scintillators, with high scintillation ($\lambda = 128$ nm for Ar, $\lambda = 175$ nm for Xe) and ionization yields. They are available in large quantities (with LAr being much cheaper) and can be purified to 1 ppt (parts per trillion)-levels. Scintillation in LAr and LXe is produced by the formation of excimer states, which are bound states of ion-atom systems. If a high electric field ($\sim 1$ kV/cm) is applied, ionization electrons can also be detected, either directly or through the secondary process of proportional scintillation. Measuring both the primary scintillation signal and a secondary process yields a method of discriminating between electron and nuclear recoils. In LAr, an additional differentiation, namely the time difference between the decay of the singlet and triplet excited states (6 ns versus 1.6 $\mu$s) is being used. An advantage of LXe is its high density (3 g/cm$^3$), which provides self-shielding and allows for compact detectors, and the high atomic number ($Z=54$, $A=131.3$), which is favorable for scalar WIMP-nucleus interactions. Moreover, since natural Xe has two isotopes with spin ($^{129}$Xe, $^{131}$Xe, at the combined level of almost 50% abundance), a liquid xenon detector is susceptible for both coherent and axial-vector WIMP-nucleus couplings.

2. The XENON10 Experiment

XENON10 is a new direct dark matter search experiment with the aim of observing the small energy released after a WIMP scatters off a xenon nucleus [1]. The simultaneous detection of ionization and scintillation in a liquid xenon (LXe) 3D position sensitive time projection chamber (TPC) allows to distinguish nuclear recoils (as produced by WIMPs and neutrons) from the dominant electron recoil background (as originated from photon and electron interactions) [15][16]. The detector has been transported from the Nevis Laboratory at Columbia University to Gran Sasso in March 2006 and has been installed in its low-background shield in mid July 2006. It has been taking data continuously and very stably since then, with a total of more than 75 live days of WIMP search data accumulated.

The dual-phase (liquid and gas) TPC is filled with 22 kg of ultra-pure liquid xenon, the active volume being defined by a teflon cylinder with an inner diameter of 20 cm and a height of 15 cm (the total active mass is 15 kg of LXe). The TPC is equipped with four wire meshes, two in the liquid and two in the gas phase. The bottom mesh serves as a cathode and the next one, positioned just below the liquid level, forms, together with a series of field shaping rings, the 15 cm drift region. The two last meshes, along with the one below the liquid level, serve to define the gas proportional scintillation region. The active xenon volume is viewed by 89 Hamamatsu R8520-06AL 1 inch square PMTs, 35 mm high. The bottom array of 41 PMTs is located below the cathode, fully immersed in LXe, and mainly detects the prompt light signal (in the following labeled S1). The 48 PMTs of the top array are located in the cold gas above the liquid, detecting the proportional light signal (labeled S2) which is created by the collision of extracted electrons with Xe atoms in the gas phase (the drift field is 0.7 kV/cm). Figure 1 shows the XENON10 detector in its low-background shield (left) as well as a picture of the top PMT array (right). The hit pattern in this array is used to reconstruct the x-y position of an event with few mm resolution. The z-coordinate is calculated from the time difference between the pulses of direct and proportional light (with a maximum of 75 $\mu$s and a resulting z-resolution of <1 mm). Typical low energy electron and nuclear recoil events detected by XENON10 PMTs are shown in Figure 2. As we will demonstrate in the next sections, the 3D position sensitivity and the self shielding of LXe, serves, along with the prompt versus proportional light ratio, as a fundamental background rejection feature.
Figure 1. (left) A view of the XENON10 TPC in its low-background shield during the initial installation. 1.6 tons of polyethylene and 34 tons of lead are used to reduce the external neutron and gamma background to insignificant levels. (right) A picture of the top photo-multiplier array (48 Hamamatsu R8520-AL PMTs) before its insertion into the inner detector chamber.

The cooling of XENON10 is provided by a pulse tube refrigerator directly in contact with the Xe gas. We have attained a very stable pressure ($\Delta P < 0.006$ atm) and temperature ($\Delta T < 0.005^\circ$C) for over six months of operation. Under these conditions the fluctuation of PMT gains is $< 2\%$. To reach the high purity required for a LXe TPC with a drift gap of 15 cm, we are continuously circulating the xenon gas through a high temperature getter. The electron lifetime inferred from recent data is $(1.8 \pm 0.4)$ ms which corresponds to a $\ll 1$ ppb (O$_2$ equivalent) xenon purity.

Figure 2. (left) Low-energy electron recoil event (photon induced), with a S1 signal of 70 photoelectrons and a S2 of $1.7\times10^4$ p.e. (right) Low-energy Xe nuclear recoil event (neutron induced), with a S1 signal of 70 photoelectrons and a S2 of $5.3\times10^3$ p.e.

3. XENON10 in situ Calibration Measurements
We have used gamma ($^{57}$Co, $^{137}$Cs) and neutron (AmBe) calibration sources, as well as neutron-activated xenon ($^{131m}$Xe, $^{129m}$Xe) to extensively calibrate the XENON10 detector at the underground laboratory. To achieve a minimum impact on WIMP search exposure time, the
passive lead and polyethylene shields were designed to allow insertion of external, encapsulated sources without exposing the detector cavity to outside, radon-contaminated air. Figure 3 (left) shows a scintillation light spectrum (S1) from a $^{57}$Co calibration. For a radius $8 < r < 9$ cm the average light yield for $122$ keV gamma rays is 374 photo-electrons (p.e.) (3.1 p.e./keV), with an energy resolution $\sigma$ of 17%. The inset shows the clear detection of the characteristic X-ray peak from the K-shell at $\sim 30$ keV. A scintillation light spectrum from a $^{137}$Cs calibration is shown on the right side of the same figure. The $662$ keV photo-absorption peak yields an average light yield of 1464 p.e. (2.2 p.e./keV) and an energy resolution $\sigma$ of 205 p.e. (14%). The light yield does not change substantially (less than 5%) for radii $r < 9$ cm.

Figure 3. (left) S1 scintillation spectrum from a $^{57}$Co calibration. The light yield for the $122$ keV photo-absorption peak is 3.1 p.e./keV. (right) S1 scintillation spectrum from a $^{137}$Cs calibration. The light yield for the $662$ keV photo-absorption peak is 2.2 p.e./keV.

On December 1, 2006, we have calibrated the XENON10 detector with an encapsulated AmBe neutron source with an activity of 200 neutrons/s. Such a calibration allows to determine the predicted WIMP signal region as well as the detector’s ability to distinguish between nuclear and electron recoils down to its energy threshold. The energy threshold was determined to be at $\sim 10$ keV nuclear recoil energy (keVr) with a light yield of 0.7 photo-electrons/keVr. In Figure 4 (left) we show a data versus Monte Carlo comparison of the energy spectrum of single elastic nuclear recoils in LXe. We note the good agreement between the data and the Monte Carlo above $\sim 10$ keVr. At the time of this writing a small amount of neutron activated xenon gas was added to the XENON10 detector. Two xenon meta-stable states, $^{131m}$Xe and $^{129m}$Xe decay emitting $164$ keV and $236$ keV gamma rays with half-lives of 11.8 days and 8.9 days, respectively. These photons allow for a more uniform energy and position calibration across the LXe active volume. Figure 4 (right) shows a preliminary S2 versus S1 plot for a subset of the activated Xe data: the two gamma lines and the anti-correlation between the S1 and the S2 signals are clearly visible.

4. Preliminary XENON10 Backgrounds, Results and Near Future Plans
The XENON10 backgrounds are dominated by gamma interactions originating from the remaining radioactivity of detector materials. In Figure 5 (left) we show the x-y-distribution of background events from a subset of WIMP search data. A radial (along with a z-axial) cut dramatically reduced the background to the level of about 1 event/kg/day/keV. The right
Figure 4. (left) A data versus MC comparison of the energy spectrum of single elastic nuclear recoils in XENON10. The data was taken during an AmBe neutron calibration on December 1, 2006. (right) S2 versus S1 signal for n-activated Xe data. The gamma lines at 164 keV and 236 keV and the S2-S1 anti-correlation are clearly visible.

Figure 5. (left) x-y position of background events for a subset of the WIMP search data. The shielding power of the dense liquid, and the advantage of 3-D position sensitivity are evident. (right) Comparison of XENON10 background data (red crosses) with Monte Carlo predictions (MC sum in solid black) from radioactivity in the PMTs, ceramic and stainless steel detector components.

side of the same figure shows a histogram of the remaining background after fiducial volume cuts, together with the result of a Monte Carlo simulation based on the measured activities of the detector and shield materials. The backgrounds can be explained by the U/Th/K/Co radioactivity in the PMTs, in the stainless steel used in the detector and cryostat, and in the signal and high voltage ceramic feedthroughs.

The sensitivity to WIMP-nucleon interactions depends on the detector’s ability to distinguish between electron and nuclear recoils, for the dominant background stems from electron recoil interactions. We have studied the XENON10 discrimination based on $^{137}$Cs gamma and AmBe neutron calibration data. Figure 6 (left) shows the electron and nuclear recoil bands in the $\log_{10}(S2/S1)$ versus S1 parameter space, along with the calculated band centroids and the $\pm 2\sigma$-
regions. These regions were determined by fitting Gaussian distributions to the data, divided in 5 keV energy intervals. For a nuclear recoil acceptance at the level of 50% between 10–40 keVr, the achieved discrimination is 99.5%. We note that XENON10 is operated at a drift field of 0.7 kV/cm, and that we expect a higher level of discrimination for a larger drift field, as will be realized in the upgraded XENON10 version.

Figure 6. (left) Electron and nuclear recoil bands in the S2/S1 versus S1 parameter space (from $^{137}$Cs and AmBe data), and the $\pm 2\sigma$-regions of the calculated band centroids. We remind the reader that the data is taken at a drift field of 0.7 kV/cm. (right) XENON10 ionization yield versus scintillation energy, for a subset ($\sim$22 live days) of the WIMP search data. The magenta and green lines correspond to the centroid of the electron and nuclear bands, as determined from calibration data.

The total statistics of the dark matter search data amounts to about 75 days of live time with a 15 kg sensitive volume. Figure 6 (right) shows a plot of $\log_{10}(S2/S1)$ as a function of energy for $\sim$22 live days, giving a total exposure of 38 kg d after cuts. The magenta and green lines correspond to the centroid of the electron and nuclear recoil bands, respectively. In the energy region 3-15 keV (10-40 keVr), zero events are observed in the 50% acceptance window of the nuclear recoil band. In the region above 15 keV energy, we observed few events in the nuclear recoil band. Our current understanding is that these are double scatter events, with one interaction in a passive region and one in the fiducial volume. Since no S2 signal is observed for scatters in passive xenon, the additional S1 signal from such a region results in a smaller $\log_{10}(S2/S1)$ ratio. We are currently testing this hypothesis with Monte Carlo simulations and comparison with calibration data, and are planning to block the passive xenon regions for the S1 light signal for an upgraded XENON10 version.

We are in the process of analyzing the complete science data set, whereby we have blinded about two-thirds of the total WIMP search data. We are developing the data quality and physics cuts, and are testing their efficiencies on calibration and non-blinded WIMP search data. We expect that the existing configuration can probe WIMP-nucleon cross sections down to $1 \times 10^{-7}$ pb for coherent WIMP-nuclei interactions. Concomitantly, we are preparing an upgrade of the XENON10 detector. Modest changes, such as the replacement of ceramic feedthroughs with lower activity ones, already in hand, the replacement of the stainless steel vessel with a vessel made of OFHC Copper, selection of low radioactivity PMTs, etc, would reduce the expected background to 0.1 events/keV/kg/day, one order of magnitude below the current level. We also expect that operation of the detector at a higher drift field will improve the nuclear versus electron recoil discrimination, and that optically masking the dead xenon regions will decrease
the number of potential leakage events. If lower backgrounds and a higher discrimination can be achieved, XENON10 could reach a WIMP-nucleon sensitivity of $2 \times 10^{-8}$ pb by 2008.

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