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RESULTS FROM THE XENON100 EXPERIMENT

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Abstract. The XENON program consists in operating and developing double-phase time projection chambers using liquid xenon as the target material. It aims to directly detect dark matter in the form of WIMPs via their elastic scattering off xenon nuclei. The current phase is XENON100, located at the Laboratori Nazionali del Gran Sasso (LNGS), with a 62 kg liquid xenon target. We present the 100.9 live days of data, acquired between January and June 2010, with no evidence of dark matter, as well as the new results of the last scientific run, with about 225 live days. The next phase, XENON1T, will increase the sensitivity by two orders of magnitude.

Keywords: dark matter, WIMP, xenon.

1. Introduction

Astronomical and cosmological observations indicate that a large amount of the energy content in the Universe is made of dark matter [1]. Particle candidates under the generic name of Weakly Interacting Massive Particles (WIMPs) arise naturally in many theories beyond the Standard Model of particle physics, such as supersymmetry, universal extra dimensions, or little Higgs models [2]. They may be observed in underground-based detectors, sensitive enough to measure the low-energy nuclear recoil resulting from the coherent scattering of a WIMP with a target nucleus [3].

The XENON dark matter project searches for nuclear recoils from WIMPs scattering off xenon nuclei. In a phased approach, experiments with increasingly larger mass and lower background are being operated underground, at the INFN Laboratori Nazionali del Gran Sasso (LNGS) in Italy [4]. XENON100 is the current phase of the XENON program, which aims to improve the sensitivity to dark matter interactions in liquid xenon (LXe) with two-phase (liquid/gas) time-projection chambers (TPCs) of large mass and low background. The extraordinary sensitivity of XENON to dark matter is due to the combination of a large, homogeneous volume of ultra pure liquid xenon as the WIMP target, in a detector which measures not only the energy, but also the three spatial coordinates of each event occurring within the active target. The ability to localise events within millimetre resolution, enables the selection of a fiducial volume in which the radioactive background is minimised.

The simultaneous detection of the Xe scintillation light (S1) at the few $\mathrm{keV_{ee}}$ level (keV electron equivalent), and ionization (S2) at the single electron level, allows to discriminate electronic recoils (ERs) from nuclear recoils (NRs), providing the basis of one of the major background techniques.

2. XENON100

2.1. Detector description

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 (Fig. 1). The primary light (S1) is detected immediately by two photomultiplier (PMT) arrays above and below the target. The light readout is based on 1"-square Hamamatsu R8520-06-Al low-radioactive PMTs with quantum efficiencies up to $\sim 35\,\%$. 98 PMTs in the top array are arranged to improve the position reconstruction, 80 PMTs on the bottom to optimise the light collection. The other 64 PMTs are located in the LXe veto to reduce the background.

Each interaction liberates electrons, which are drifted upwards across the TPC by an electric field ($\sim 0.53\,\mathrm{kV/cm}$) to the liquid-gas interface with a speed of about 2 mm/µs. These electrons are then extracted into the gas phase by a strong extraction field. In the gas phase, the electrons generate very localised secondary scintillation light (S2), which can be used to determine the horizontal position of the interaction vertex with a resolution $< 3\,\mathrm{mm}$ (1σ). The time difference between these two signals gives the depth of the interaction in the TPC with a resolution of 0.3 mm (1σ).

The event positions can be fully reconstructed and used to federalise the target volume in order to drastically reduce the radioactive background from external sources. The high ionization density of nuclear recoils (NRs) in LXe leads to larger S1 and smaller S2 signals compared to electron recoils (ERs). The simultaneous measurement of charge and light provides powerful discrimination between NR signals and ER background events via the ratio S2/S1.

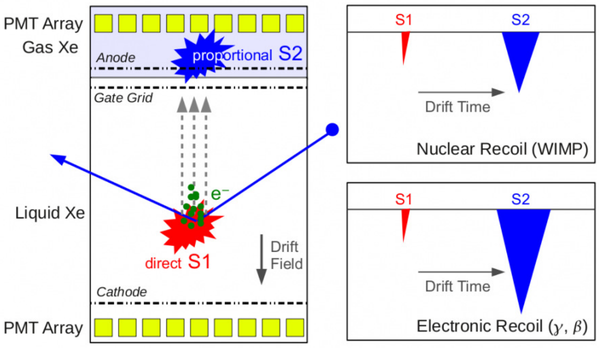

FIGURE 1. Principle of a two-phase liquid xenon TPC. A particle generates primary scintillation light (S1) and ionization electrons. These are drifted upwards by an electric field and detected via secondary scintillation light in the gas phase (S2). The S2 hit pattern (xy) and the drift time (z) give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

FIGURE 2. XENON100 with opened shield door. The circular copper pipe around the detector is used for inserting calibration sources from outside the shield. The Pb brick visible at the front is necessary to block gamma rays from the AmBe source during neutron calibration.

2.2. DETECTOR BACKGROUNDS

The background in XENON100 comes mainly from external sources and from the materials used for the construction of the detector itself.

In order to reduce the background from the radioactivity in the experiment's environment, in the laboratory walls, etc. [5], a passive shield has been installed. An improved version of the XENON10 shield [6] was required to increase the sensitivity of the XENON100 experiment. The detector is surrounded (from inside to outside) by 5 cm of copper, followed by 20 cm of polyethylene, and 20 cm of lead, where the innermost 5 cm consist of lead with low ^{210}Pb contamination [7]. The entire shield rests on a 25 cm thick slab of polyethylene. An additional outer layer of 20 cm of water and polyethylene has been added on top and on 3 sides of the shield to reduce the neutron background further. Figure 2 shows a picture of the XENON100 detector in front of its shield. In order to minimise the radioactive background in the detector, the cryogenic system is located outside the passive shield.

To reduce the radioactivity from the detector and the shielding materials, radioactivity screening was performed with a 2.2 kg high purity Ge detector in an ultra-low background Cu cryostat and Cu/Pb shield, operated at LNGS [8]. The radioactive contaminations of each material screened can be found in reference [7].

The radioactivity of all the components has been measured and is used as input for detailed Monte-Carlo simulations of the γ and neutron background of the experiment. Gammas from the decay chains of the radioactive contaminants in the detector materials dominate the electron recoil background. The activity of the PMTs is the major contributor to the current XENON100 electron recoil background (about 65 % of the total background from all detector and shield materials). This background in XENON100 is 6×10^{-3} dru. After 99 % electron recoil rejection we obtain a conservative background rate of 6×10^{-5} dru.

A potentially dangerous background for XENON100 is the gamma background from the decay chain of ^{222}Rn daughters inside the shield cavity. The average measured radon activity in the LNGS tunnel is about 350 Bq/m^3. Therefore, the shield cavity is constantly flushed with nitrogen gas when the shield door is closed. The ^{222}Rn concentration in the cavity is continuously monitored and the measured values are at the limit of the sensitivity of the radon monitor itself. Without the veto cut, the background rate from 1 Bq/m^3 of ^{222}Rn in the shield is 6×10^{-3} dru for the entire target mass of 62 kg and 2×10^{-4} dru in the 30 % kg FV. This background is less than 2 % of the background from the detector and shield materials. Moreover, the measured radon concentration is well below 1 Bq/m^3.

There is no long-lived radioactive xenon isotope, with the exception of the potential double beta emitter ^{136}Xe, but its half-life is so long that it does not limit the sensitivity of the detector. Another LXe intrinsic background is due to ^{85}Kr, which is a beta emitter with an endpoint of 687 keV and a half-life of 10.76 years.

Its concentration in the detector can be measured using a second decay mode (in a metastable state of Rb) with a 0.454 % branching ratio. Commercially available xenon gas has a concentration of natural krypton at the ppm level and ^{85}Kr has an isotopic abundance of ^{85}Kr/^{nat}Kr $\sim 2 \times 10^{-11}$. For the ^{85}Kr-induced background to be subdominant, the fraction of ^{nat}Kr in Xe must be at the level of 100 ppt. A ^{nat}Kr/Xe ratio of 100 ppt would contribute a rate of $\sim$ 2 mdru from ^{85}Kr [9]. To reduce the Kr level in Xe, a small-scale cryogenic distillation column [10] was

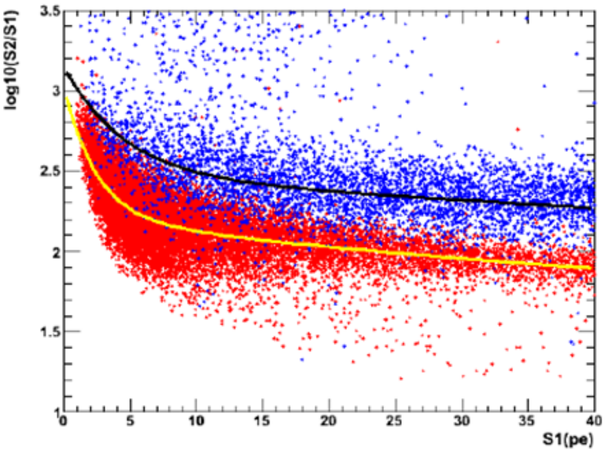

Figure 3. Electronic (blue dots) and nuclear (red dots) recoil bands in the $\log_{10}(S2/S1)$ vs. energy space. The electronic recoil band is obtained with ^{60}Co and ^{232}Th calibrations, performed weekly during a dark matter search run. The nuclear recoil band is measured with an AmBe source shielded by 10 cm of lead. This calibration is performed at the beginning or at the end of a dark matter search run, because of neutron activation of Xe and other materials.

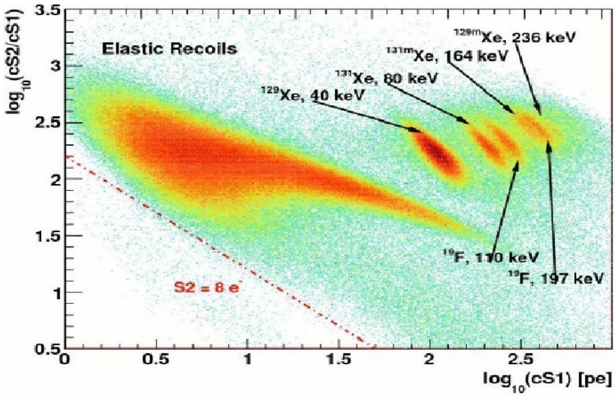

Figure 4. Results of AmBe calibration data. Besides the NR recoil band due to neutron elastic scatter off Xe nuclei, this calibration provides additional gamma lines from neutron activation of xenon and fluorine (in the teflon) nuclei at 40 keV (^{129}Xe), 80 keV (^{131}Xe), 110 keV (^{19}F), 164 keV (^{131m}Xe), 197 keV (^{19}F) and 236 keV (^{129m}Xe).

produced and integrated into the XENON100 system underground. The column is designed to deliver a factor 1000 in Kr reduction in a single pass.

The nuclear recoil background is estimated by Monte-Carlo simulations and is based on the measured radioactivity concentrations. It takes into account the neutron spectra and the total production rates from spontaneous fission and (α, n) reactions in the detector, the shielding materials, and the surrounding concrete-rock, calculated with a modified SOURCES4A code [11]. The muon flux at the 3600 mw.e. Gran Sasso depth is 24 muons/m^2/day. Muons will produce neutrons in the shielding materials due to electromagnetic and hadronic showers and through direct spallation.

High energy muon interacting in the rock-concrete can produce highly penetrating neutrons with energies up to a few GeV. The impact of muon-induced neutrons is obtained from simulations and contributes 70 % to the total NRs background.

2.3. Detector calibrations

To characterise the detector performances and its stability in time, calibration sources are regularly inserted in the XENON100 shield through a copper tube surrounding the cryostat (see Fig. 2). While the vertical position of sources is restricted to the TPC centre, they can be placed at all azimuthal angles.

The electronic recoil band in $\log_{10}(S2/S1)$ vs. energy space defines the region of background events from β- and γ-particles (blue dots in Fig. 3). It is measured using the low energy Compton tail of high-energy γ-sources such as ^{60}Co and ^{232}Th. In the 225 day dark matter search, the amount of electronic recoil calibration data taken is a significant increase over that taken during the 100.9 day dark matter search. The detector response to single scatter nuclear recoils, the expected signature of a WIMP scattering off a nucleus, is measured with an AmBe (α, n) source (red dots in Fig. 3). This source is shielded by 10 cm of lead in order to suppress the contribution from its high energy gamma rays (4.4 MeV). The comparison of the charge/light ratio allows to define a region where most of the neutrons are, and only few gammas. The discrimination power is $\sim 99.5\,\%$ at low energies for 50 % neutron acceptance. Besides the definition of the nuclear recoil band and a benchmark WIMP search region, the AmBe calibration provides additional gamma lines from inelastic scattering as well as from xenon or fluorine (in the Teflon) neutron activation at 40 keV (^{129}Xe), 80 keV (^{131}Xe), 110 keV (^{19}F), 164 keV (^{131m}Xe), 197 keV (^{19}F) and 236 keV (^{129m}Xe). These lines are clearly visible in Fig. 4 as ellipsoids over the nuclear recoils band due to neutron elastic scatters off xenon nuclei.

In order to get a uniform proportional scintillation $S2$ signal, the liquid-gas interface has to be adjusted at the optimal distance from the anode to optimise the $S2$ resolution. This levelling was performed at the beginning of the run with a ^{137}Cs source, by varying the overall liquid xenon level until the best resolution of the full absorption $S2$ peak was found. After detector levelling, two independent effects remain that have an impact on the size of the proportional scintillation $S2$ signal from the charge: a) the absorption of electrons as they drift (finite electron lifetime), leading to a z-dependent correction, b) the reduced $S2$ light collection efficiency at large radii, non-functional PMTs, quantum efficiency differences between neighbouring PMTs, as well as non-uniformities in the proportional scintillation gap, leading to an $S2$ correction that depends on the (x,y)-position of the $S2$ signal. Regular

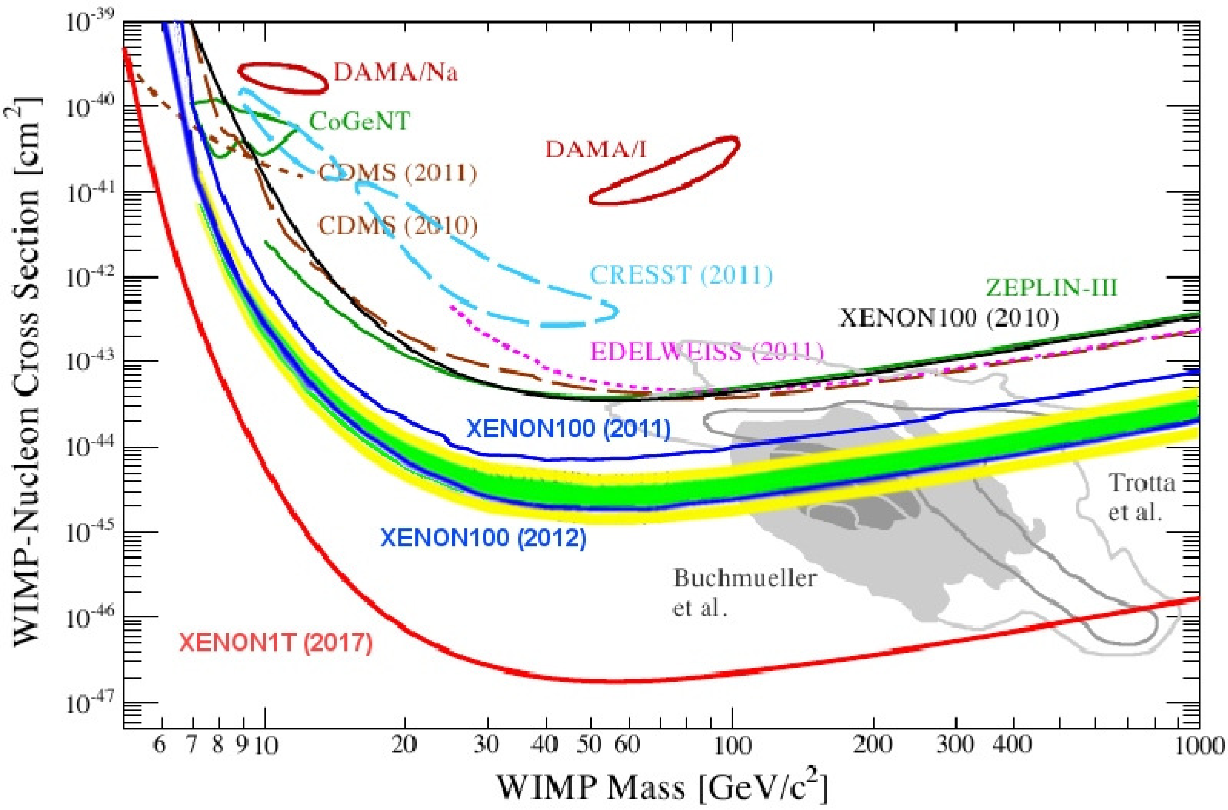

Figure 5. New result on spin-independent WIMP-nucleon scattering from XENON100: The expected sensitivity of this run is shown by the green/yellow band ($1\sigma/2\sigma$) and the resulting exclusion limit (90 % CL) in blue. For comparison, the XENON100 exclusion limit of the last 100.9 day run and other experimental results are also shown, together with regions ($1\sigma/2\sigma$) preferred by supersymmetric (CMSSM) models. The projected sensitivity for XENON1T is shown in red.

^{137}Cs calibration runs are taken in order to determine the mean lifetime for electrons transversing the liquid xenon volume (free electrons are removed through ionization of impurities). The LXe is continuously purified through a hot getter in order to reduce the impurity level. In the 100.9 day dark matter search, the mean electron lifetime increased from 230 µs to 380 µs, while in the last run (225 days) it increased (constantly, if the maintenance periods are not taken into account) from around 300 µs to 650 µs.

2.4. Data analysis

The data used in the analysis were selected from periods with stable detector operating conditions. We excluded from the analysis all periods with xenon pressure and temperature values that were more than 5 sigma away from the average value. After this selection, other parameters were found to be stable during the whole science run. The radon concentration in the XENON100 room and inside the shield cavity were measured using a dedicated radon monitor, and the concentration was stable for the whole period.

Two parallel analyses were performed to interpret these data in a spin-independent WIMP-nucleon interaction framework. The energy region used for both analyses was $(4 \div 30)$ PE in $S1$ corresponding to $(8.4 \div 44.6)\,\mathrm{keV_{nr}}$. This energy region was lowered from 4 PE to 3 PE for the analysis of the last run (225 days). Before unblinding, it was decided to use the Profile Likelihood analysis method [12] as the primary interpretation method which does not employ a fixed discrimination in $S2/S1$ parameter space. A cut-based analysis was also performed in [13] to cross check the results.

The criteria applied to the science data to select candidate events in the region of interest are grouped into: data quality cuts, energy selection and a threshold cut on $S2$, selection of single scatter events, consistency cuts, selection of the fiducial volume, and selection of the signal region for the cut-based analysis [14].

3. Results

3.1. 100 live days DM search

The dark matter data analysed for this run was acquired between January 13 and June 8, 2010. About 2 % of the exposure was rejected due to variations in detector operation parameters. In addition, 18 live days of data taken in April were rejected due to an increased electronic noise level. Removing all the calibration runs during the data-taking period, this led to a dataset of 100.9 live days. The expected background in the WIMP search region is the sum of the Gaussian leakage from the ER background, of the non-Gaussian leakage, and of the NRs from neutron interactions. The total background prediction for 99.75 % ER rejection, 100.9 days of exposure and 48 kg fiducial mass is (1.8 ± 0.6) events.

After unblinding the pre-defined WIMP search region, a population of events was observed that passed the $S1$ coincidence requirement only because of the correlated electronic noise. These events are mostly found below the $S1$ analysis threshold, with 3 events from this population leaking into the WIMP search region close to the 4 PE lower bound. This population was identified and rejected with a cut that takes into account the correlated pick-up noise. Once they have been removed, 3 events pass all quality criteria for single-scatter NRs and fall in the WIMP search region. Given the background expectation, the observation of 3 events does not constitute evidence for dark matter, as the chance probability of the corresponding Poisson process resulting in 3 or more events is 28 %.

3.2. 225 live days DM search

The last run of XENON100 represents 224.6 live days of dark matter search data. Purification through a dedicated krypton removal column saw the intrinsic background of the liquid xenon drop by more than a factor of 10. In the last run, for unblinded data (above 99.75 ER rejection) and a 30 kg fiducial mass, about 2 single-scatter events are observed per day below 30 PE in $S1$. These values illustrate the low count rate in the electron recoil background in XENON100 and the improvement made with the reduction of the intrinsic krypton background. Moreover, the trigger threshold was lowered from 300 PE to 150 PE in $S2$.

The dark matter data analysed for this run was acquired over 13 months in 2011 and 2012. A blind analysis of 224.6 live days $\times$ 34 kg exposure yielded no evidence for dark matter interactions. The two candidate events observed in the pre-defined nuclear recoil energy range of $6.6 \div 30.5\,\mathrm{keV_{nr}}$ are consistent with the background expectation of (1.0 ± 0.2) events [15].

4. XENON1T

In parallel with the successful operations of XENON100, the Collaboration has already designed the next generation detector: XENON1T. The detector is based on an LXe TPC with a fiducial mass of 1 ton and a total mass of 2.4 tons of LXe, viewed by low radioactivity photomultiplier tubes and housed in a water Cherenkov muon veto at LNGS. Detailed simulation studies informed by results from previous XENON and other LXe detectors indicate that an increase in the light yield of XENON1T relative to XENON100 is achievable by adopting relatively modest modifications to the design of the TPC, such as greater coverage of non-reflective surfaces with PTFE of near unity reflectivity, greater optical transmission of electrode structures and, especially, greater quantum efficiency of photomultiplier tubes. The background can be reduced through the selection of every component used in the experiment, based on an extensive radiation screening campaign, using a variety of complementary techniques and dedicated measurements. Moreover the self-shielding of LXe is exploited to attenuate and moderate radiation from material components within the TPC and simultaneously a fiducial volume will be defined, thanks to the TPC event imaging capability. The experiment aims to reduce the background from all expected sources such that the fiducial mass and the low energy threshold will allow XENON1T to achieve unprecedent sensitivity. With 2 years live-time and 1.1 ton fiducial mass, XENON1T reaches sensitivity of $2 \times 10^{-47}\,\mathrm{cm^2}$ at 90 % CL for $50\,\mathrm{GeV/c^2}$ WIMPs, as shown in Fig. 5.

Acknowledgements

References

[1] N. Jarosik et al., Astropart. J. Suppl. **192**, (2011) 14; K. Nakamura et al., (Particle Data Group), J. Phys. **G 37**, (2010) 075021.

[2] G. Steigman and M. S. Turner, Nucl. Phys **B 253**, (1985) 375; G. Jungman, M. Kamionkowski and K. Griest, Phys. Rept. **267**, (1996) 195.

[3] M. W. Goodman and E. Witten, Phys. Rev. **D 31**, (1985) 3059.

[4] www.lngs.infn.it

[5] M. Haffke et al., Nucl. Instr. Meth. Phys. Res. Sect. **A 643**, (2011) 36.

[6] E. Aprile et al., (XENON10 Collaboration), Astropart. Phys. **34**, (2011) 679.

[7] E. Aprile et al., (XENON100 Collaboration), Astropart. Phys. **35**, (2011) 43.

[8] G. Heusser, M. Laubenstein and H. Neder, Radionuclides in the Environment **8**, (2006) 495.

[9] E. Aprile et al., (XENON100 Collaboration), Phys. Rev. **D 83**, (2011) 082001.

[10] http://www.tn-sanso.co.jp/en/

[11] R. Lemrani et al., Nucl. Instr. Meth. **A 560**, (2006) 454.

[12] E. Aprile et al., (XENON100 Collaboration), Phys. Rev. **D 84**, (2011) 052003.

[13] E. Aprile et al., (XENON100 Collaboration), Phys. Rev. Lett. **107**, (2011) 131302.

[14] E. Aprile et al., (XENON100 Collaboration), arXiv:1207.3458v2

[15] E. Aprile et al., (XENON100 Collaboration), arXiv:1207.5988