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The XENON Dark Matter project: from XENON100 to XENON1T

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Abstract

The XENON Collaboration is searching for Dark Matter interactions in a liquid xenon target. The XENON100 detector, a dual phase xenon Time Projection Chamber employing 161 kg of liquid xenon, started the first science run at the Laboratori Nazionali del Gran Sasso in Italy in 2009. It provided limits on the spin-independent and spin-dependent interaction cross sections of Weakly Interacting Massive Particles (WIMPs), and the couplings of solar axions and galactic axion-like particles. We present these results and the status of the successor experiment, XENON1T. The new detector, currently under construction and starting data taking in 2015, will employ 3.3 tons of liquid xenon, reaching a sensitivity to spin-independent WIMP-nucleon cross section of the order of 10^{-47} cm².

Keywords: Dark Matter, WIMP, Axions, dual-phase xenon Time Projection Chamber

1. Introduction

Astrophysical observations provide evidence that Dark Matter constitutes the largest fraction of the mass in the Universe, yet its nature is still unknown. Weakly Interacting Massive Particles (WIMPs) are well motivated candidate particles that can explain the observed relic density and can be accommodated by several extensions of the Standard Model [1]. WIMPs can occasionally interact elastically with nuclei and therefore be “directly-detected” by observing the small recoils of these nuclei in a target material. Since such interactions exceedingly rare, the detection requires deep underground experiments with low radioactive background and high sensitivity to small energy deposits [2].

The XENON Collaboration pursues a phased approach to WIMP direct detection employing ultra-pure liquid xenon as both target and detection medium. Liquid xenon (LXe) has ideal properties as a dark matter target [3]. The high mass of the xenon nucleus is favourable to scalar interactions and the presence

of two isotopes with unpaired neutrons (¹²⁹Xe: spin-1/2, 26.4% and ¹³¹Xe: spin-3/2, 21.2%) ensures sensitivity to spin-dependent WIMP-nuclei couplings. The high density (3 g/cm³) and high atomic number (Z=54, A=131.3) allow to build self-shielding, compact dark matter detectors. As a detection medium, it has high scintillation and ionisation yields because of its low ionisation potential.

The XENON detectors, located at the Laboratori Nazionali del Gran Sasso (LNGS) in Italy, are dual-phase (liquid and vapour xenon) Time Projection Chambers (TPC) of increasing target mass and reduced background. The XENON100 detector is the current phase of the programme. It has been recording data since 2008, being the longest operated dual phase xenon TPC so far. Its recent scientific production is discussed in Sec. 2. At the same time, the Collaboration is building the successor experiment at LNGS, XENON1T, which will start data-taking in 2015. The new detector and the status of its construction is described in Sec. 3.

2. Results from the XENON100 experiment

The XENON100 detector is described in detail in [4]. It is a cylindrical (30.6 cm diameter, 30.5 cm height)

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dual-phase TPC enclosing a LXe target mass of 62 kg. An additional 99 kg of the same high-purity LXe, optically separated from the target volume, is instrumented as an active scintillator veto. The prompt scintillation produced in the two volumes and the proportional scintillation from the ionisation electrons in the TPC are measured by a total of 224 low background VUV-sensitive PMTs. The dual phase TPC configuration allows for the rejection of the electronic recoils from the ratio between the scintillation and the ionisation signal. In addition, the full three-dimensional reconstruction of the interaction vertex allows for multiple scattering rejection and volume fiducialisation.

The latest WIMP search results released in 2012 [5] were based on 34 kg fiducial volume and 224.6 live days of exposure. From the same data sample and using the same analysis methods [6] we extracted limits on the spin-dependent (SD) WIMP-nucleon couplings [7] and recently also limits on models with Axions and Axion-Like Particles [8].

Spin-dependent WIMP-nucleon couplings

To derive limits on the SD WIMP-nucleon cross sections, we assumed three different models for the nucleus structure functions: the choice of the model affects especially the interpretation of the limit on the WIMP-proton coupling. However the odd isotopes of xenon provide the best sensitivity on the WIMP-neutron coupling, and the resulting limits in the three cases differ less than a factor of 2 [7]. Fig. 1 shows the limits in the case of the Menendez *et al.* [9] model. The limit on the WIMP-neutron coupling is still the most stringent to date, also if the other two models are taken into account.

Axions and Axion-Like Particles

Axions are subatomic particles initially proposed in order to find a solution to the strong CP problem of the Standard Model and are still considered in some extensions, for example the DFSZ and KSVZ models (see references in [8]). Axion-Like Particles (ALPs) are subatomic particles proposed in several extensions of the Standard Model, though they do not necessarily relate to the strong CP problem. The models foresee a coupling of these particles to photons ($g_{A\gamma}$), electrons (g_{Ae}) and nuclei (g_{AN}), which may give rise to observable signatures in detectors. In a liquid xenon detector, the coupling g_{Ae} may be tested via scattering off the electron of a xenon atom, the so-called axio-electric effect in analogy to the photoelectric process.

The Sun can be a source of axions and ALPs with a production rate dictated by the same coupling constants.

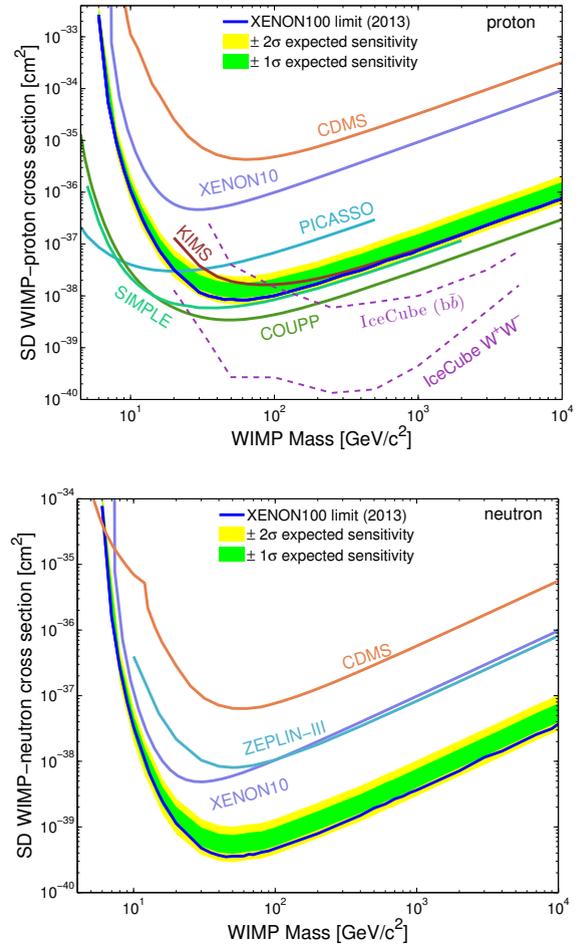


Figure 1: XENON100 90% C.L. upper limits on the WIMP spin-dependent cross section on protons (top) and neutrons (bottom) using Menendez *et al* [9]. The 1σ (2σ) uncertainty on the expected sensitivity of this run is shown as a green (yellow) band. See [7] and references therein.

In this framework, detectors on Earth can infer the coupling constant by observing this flux of “solar axions”. Fig. 2 shows the upper limit on the coupling g_{Ae} set by the search for *solar axions* in XENON100 science data, as reported in [8].

ALPs can have also been generated via a non-thermal production mechanism in the early universe and their relic density can now constitute the observed Dark Matter. In this picture, the search in XENON100 data set also a competitive limit on the axion-electron coupling g_{Ae} , as shown in Fig. 3.

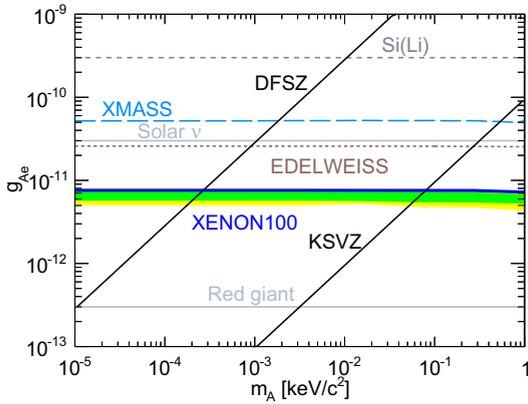


Figure 2: The XENON100 limits (90% CL) on the g_{Ae} coupling of solar axions is indicated by the blue line. The green (yellow) bands show the 1σ (2σ) expected sensitivity, based on the background hypothesis. See [8] and references therein.

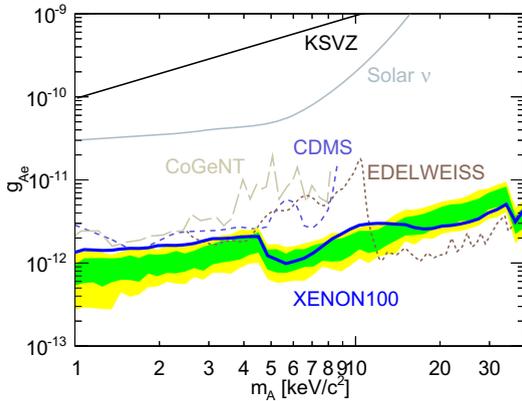


Figure 3: The blue line shows the XENON100 limit (90% CL) on ALP coupling to electrons as a function of the mass, under the assumption that ALPs constitute all the dark matter in our galaxy. The 1σ (2σ) expected sensitivity is shown by the green (yellow) bands. See [8] and references therein.

Study of the detector response to nuclear recoils

A comparison between a Monte Carlo simulation of the neutron exposure from an $^{241}\text{AmBe}(n, \alpha)$ neutron source and the equivalent calibration data is reported in [10]. The generation of both S1 and S2 signals were modelled, respectively, taking into account all the recent measurements of the relative scintillation efficiency \mathcal{L}_{eff} and searching for the best fit value for the charge yield Q_y . An absolute spectral matching is achieved with a source strength that has been independently measured at the Physikalisch-Technische Bundesanstalt (PTB), the German National Metrology Institute, after the use during the science run.

Fig. 4 shows the comparison of the S2 spectrum be-

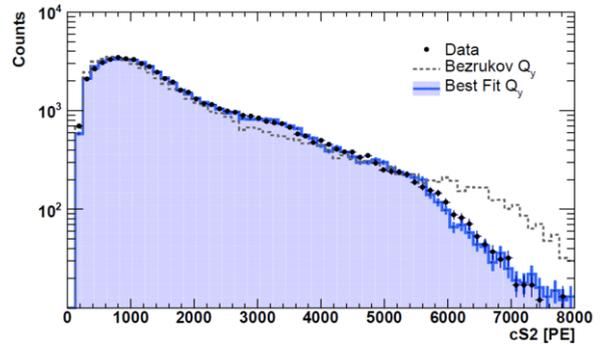


Figure 4: Comparison between the S2 spectrum from data (black dots) and the Monte Carlo spectrum (blue histogram) as obtained from the optimisation of Q_y . See [10] and references therein.

tween data and the Monte Carlo simulation after the Q_y optimisation.

In Fig. 5 the S1 spectrum as obtained from data is compared with the spectra obtained by Monte Carlo simulations with the best fit value for \mathcal{L}_{eff} and the most recent measurements of this quantity.

3. The XENON1T detector

The construction of XENON1T in Hall B at LNGS started in mid-2013. The water tank that will house the detector, the support structure inside and a service building next to the water tank have been completed (Fig. 6). Most of the cryogenics instrumentation as well as the xenon storage and purification systems have been already realised and they have been installed in the service building in Summer 2014. In the same period the

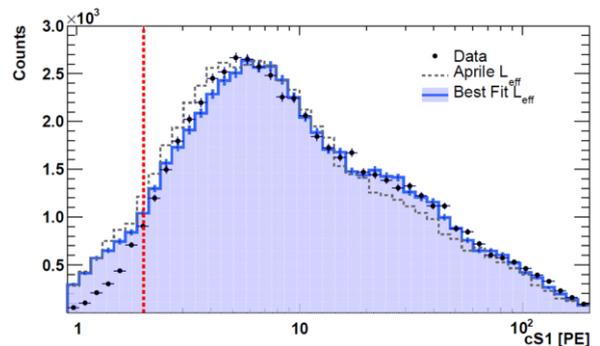


Figure 5: Fit of the simulated S1 spectrum to data (black points). The blue Monte Carlo spectrum is obtained using the \mathcal{L}_{eff} from the optimisation process, while the grey dashed line shows the spectral shape using the most recent measurements of \mathcal{L}_{eff} . See [10] and references therein.

cryostat and the UHV pipe already equipped with all the services for the detector (HV and signal cables, xenon cryogenics and recirculation pipes) have been successfully installed, while the installation of the TPC will take place in the first months of 2015. The commissioning and the beginning of the first science run of the new detector is expected for the second half of 2015.



Figure 6: Status of the XENON1T construction as of Summer 2014. (top) Photograph The XENON1T service building and water tank in Hall B at LNGS. (bottom) Photograph of the XENON1T cryostat hanging from the support structure inside the water tank: the inner vessel and the top flange of the outer vessel are visible. In the background also the UHV pipe for all the detector services is visible, going from the cryostat to the hole in the water tank on the left side of the picture.

XENON1T will employ more than 3 tons of LXe, with a fiducial mass of about 1 ton. The design is shown in Fig. 7. The TPC has a diameter and a drift length

of about 1 m, and it is designed in order to achieve a uniform electric field of 1.0 kV/cm. This is extremely challenging and required a detailed calculation of the electric field in all the regions of the TPC and special attention in the production process of the meshes and other electrodes. A custom-made feed-through has been engineered to service the cathode with the necessary high voltage (~ 100 kV). The possibility to achieve a stable condition with such a high electric field has been proved with a Demonstrator TPC built and operated at Columbia University.



Figure 7: Drawing of the XENON1T detector. The TPC and the top and bottom PMT array are visible inside the inner vessel of the cryostat. The outer vessel is larger to allow for an upgrade, XENONnT, after two years of data-taking.

XENON1T is instrumented with 248 3"-diameter Hamamatsu R11410-21 PMTs. These PMTs are a special development from Hamamatsu optimised for the detection of XENON scintillation light (QE between 36% and 40% at 178 nm wavelength) and low radioactivity. All the PMTs as well as all the components of the detectors have been screened to verify that they fulfil the stringent low radioactivity requirement. Due to the xenon self-shielding capability, the expected background rate in the fiducial volume and in the energy range of WIMP searches, originated by the detector materials radioactivity, is less than 0.25 events per year. In

the fiducial volume additional intrinsic sources of background are the impurities diluted in the liquid xenon. Most of the impurities species are efficiently removed by the recirculation through a hot getter. Noble gasses impurities, especially the β -emitter ^{85}Kr isotope, are removed by cryogenic distillation. The XENON1T distillation column will reduce the krypton concentration in the liquid xenon below 0.5 ppt. This translates to a background rate in the WIMP search region from intrinsic sources smaller than 0.15 events/year.

The cryostat is suspended within the 9.6 m diameter water tank that is instrumented as a Cherenkov muon veto. The role of the water tank is one the one hand to shield neutron and γ -ray background from the underground rock cavern and on the other hand to detect the passage of muons in the proximity of the detector, in order to reduce the background from muon-generated neutrons. The background from this source is predicted negligible (< 0.01 events/year).

The muon veto, the extensive material screening campaign, the reduction of the intrinsic background coming from Kr and Rn contamination and the self-shielding properties of liquid xenon allow to achieve the goal of less than 1 background event during a 2-years exposure. With this exposure the experiment will reach a sensitivity to spin-independent WIMP-nucleon cross sections of $\sim 2 \times 10^{-47} \text{ cm}^2$ at 90% CL in the case of a WIMP mass of $50 \text{ GeV}/c^2$.

4. Conclusions and prospects

The XENON100 experiment recently released new limits of the spin-dependent WIMP-nucleon cross-sections and, in the framework of Axion and Axion-Like Particle models, set the constraints for the coupling between these particle and electrons. The detector is still taking data and a study of novel calibration techniques is ongoing. The successor experiment XENON1T will improve the sensitivity by two order of magnitude after two year of data-taking. The construction of XENON1T is well underway and the first science run will start in 2015. The outer vessel of the cryostat and all the systems already designed in view of an upgrade, XENONnT. This upgrade will employs about 7 tons of liquid xenon and allow to achieve a sensitivity on the spin-independent WIMP-nucleon cross section of few times 10^{-48} cm^2 .

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