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First Limits on WIMP Dark Matter from the XENON10 Experiment

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Abstract. XENON10 is a dual phase liquid/gas xenon Time Projection Chamber (TPC) for the direct search of Weakly Interacting Massive Particle (WIMP) Dark Matter (DM). The detector, located in the Gran Sasso National Laboratory in Italy, aims at measuring the recoil energy from elastic WIMP-nucleus scattering. It distinguishes electronic interactions (gamma and beta backgrounds) from nuclear recoils based on a different ratio in yields of ionization charge and scintillation light. This discrimination technique reduces background by a factor of 200 – 1000 in the energy range of interest, at a nuclear recoil acceptance of 50%. Background is further reduced by the self-shielding properties of liquid xenon, as the 3D position resolution of the TPC is used to define an inner fiducial volume of low background. XENON10 was extensively calibrated with gamma and neutron sources. A blind search, with data cuts fixed a priori based on calibration data and 16 days of unblinded background data, had an exposure of 136 kg days at a fiducial mass of 5.4 kg. We report our first upper limit on WIMP DM interactions of 8.8×10^{-44} cm^2 for a WIMP mass of 100 GeV/c^2, which is a factor of 2.3 below the best previous limit.

Some 20%–25% of the matter and energy content of the universe consists of non-baryonic cold Dark Matter (DM), the nature of which is unknown. Theories based on supersymmetry (SUSY) predict neutralinos as a natural DM candidate [1, 2]. These hypothetical particles would act as WIMPs, with very small interaction cross-sections with matter and masses in the range of about 10^{1-3} GeV/c^2. WIMPS are also predicted by theories of Extra Dimensions and Little Higgs models [3, 4]. Direct search for these particles aims at measuring the recoil energy from elastic WIMP-nucleus scattering in a sensitive detector with very low background and/or good background discrimination. The typical impact velocity of WIMP particles from the Milky Way Dark Matter halo is thought to be of a similar size as the orbital speed of the Sun around the galactic center, which is ~ 230 km/s. The expected energy distribution is a steeply falling featureless spectrum. With its high atomic mass ($A = 131.3$), Xenon is a very effective target for spin-independent WIMP-nucleon interactions, which scale proportional to A^2. At large momentum transfer, the coherence of the scattering process breaks down, and the elastic scattering cross-section is correspondingly reduced. For a WIMP mass of 100 GeV/c^2 and xenon target nuclei, the energy range of interest is limited to $\lesssim 50$ keV, with the largest power at low energies: there is a similar rate contribution in 5–15 keV as in 15–50 keV. Natural xenon also contains about 50% of isotopes with unpaired neutrons, resulting in significant spin-dependent sensitivity as well.

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[1] On behalf of the XENON Collaboration

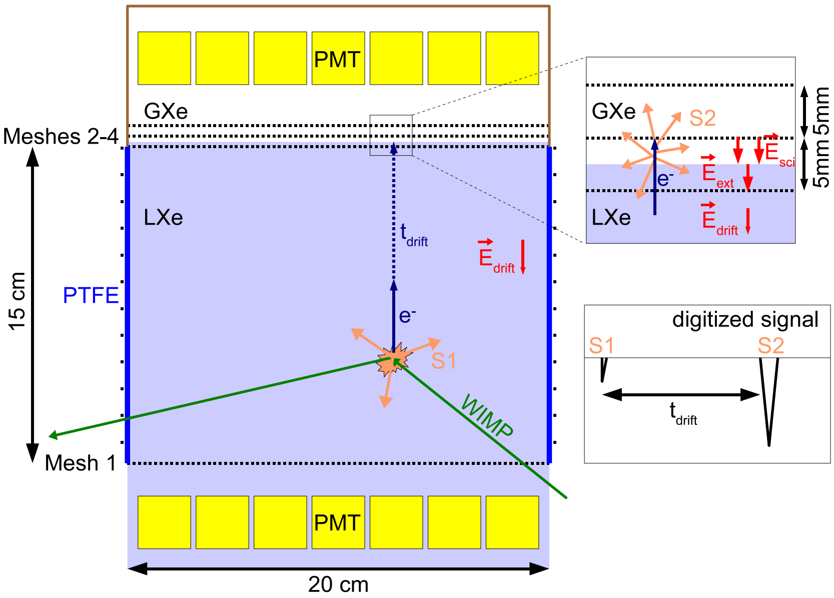

Figure 1. Measurement principle of XENON10

XENON10 is a position-sensitive dual-phase xenon TPC, viewed by two arrays of photomultiplier tubes (PMTs) on the top and bottom of the detector [5]. Fig. 1 shows the principle of operation. The dense liquid (2.85 g/cm^3) in the sensitive volume provides a compact target for WIMP and other interactions, which produce primary scintillation (signal S1) and electron-ion pairs. The electrons drift upward in a field of 0.7 kV/cm, applied between the cathode (mesh 1) on the bottom and mesh 2 on the top of the sensitive volume. A strong field ($E_{ext} \approx 5$ kV/cm in the liquid) between meshes 2 and 3 extracts the electrons from the liquid into the gas phase with full efficiency. In the low-density environment of the xenon vapor, the field is nearly twice higher and drifting charges give rise to proportional scintillation. With a light yield of a few hundred photons / electron, the resulting signal S2 is sensitive to single electrons. Hence the low energy threshold of 4.5 keV for nuclear recoils is given by the light collection efficiency for S1. The dual phase mode [6] allows both primary scintillation and ionization to be measured with the same light readout system. The large S2 is used for x/y position reconstruction by fitting simulated light response matrices to the observed hit pattern on the top PMT array, shown in Fig. 2. Fitting is based on chi-square minimization or a neural network approach. The z-coordinate is given by the time difference between S1 and S2 and the constant drift velocity, which is measured in situ. The 3D position sensitivity allows us to select single site interactions as well as a reduced fiducial volume of low background, using the self-shielding of LXe due to its large atomic number (54). XENON10 is described in detail in ref. [7].

The other main background discrimination is based on the ratio of ionization/scintillation, i.e., S2/S1, which is distinctly different for interactions with electrons, resulting in low ionization density and large S2/S1, versus nuclear recoils of high ionization density (i.e., large recombination) and small S2/S1. Fig. 3 shows an example of the discrimination power. In our analysis, we subtract the energy-dependent mean $\mathrm{Log}_{10}(S2/S1)$ of the electron recoil band to obtain $\Delta\mathrm{Log}_{10}(S2/S1)$ for all events. Calibration of S1 and S2 for electronic interactions and nuclear recoils was achieved with external and internal (using meta-stable levels of Xe-129 and Xe-131 after neutron activation) gamma-ray sources and with an AmBe neutron source. PMT gains were measured with LED light pulses.

We undertook a blind search for WIMP-nucleon interactions based on *a priori* defined data

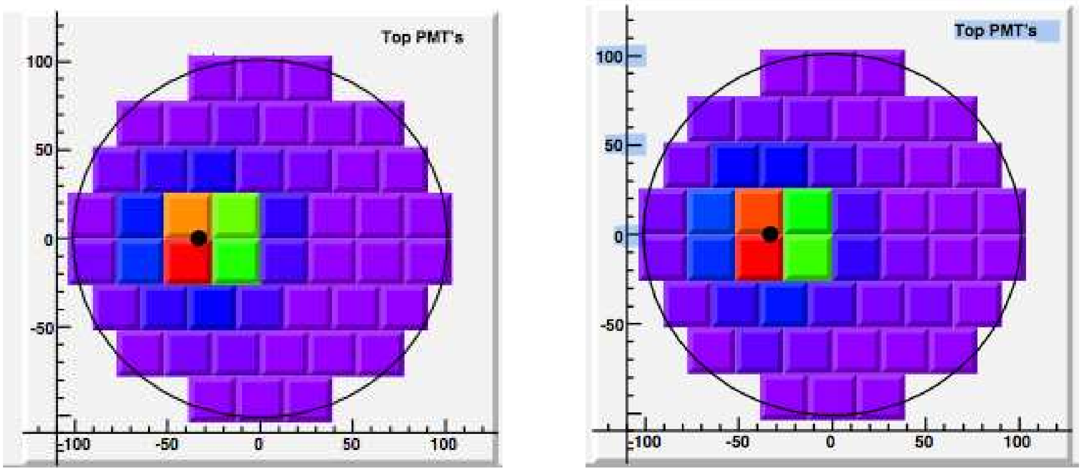

Figure 2. S2 patterns on the top PMT array [9]. Left: data. Right: Monte Carlo simulation with closest fit to data. The black dot indicates the reconstructed or simulated x/y position.

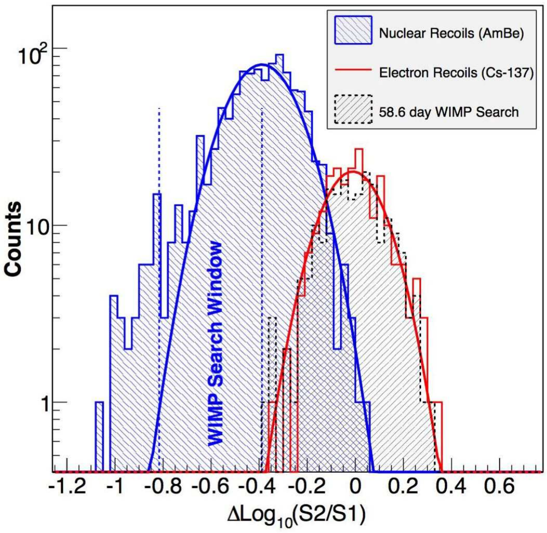

Figure 3. Histogram of the $\Delta\log_{10}(S2/S1)$ ratio, overlaying data from neutron calibration (AmBe), gamma-ray calibration (Cs-137), and from the Xenon10 WIMP search for an energy bin of 6.7–9.0 keV nuclear recoil equivalent energy. Overplotted are the best fit Gaussian functions. The nuclear recoil acceptance (WIMP Search Window) is defined by the two vertical lines, which are the -3σ and mean from a Gaussian fit to the nuclear recoil $\Delta\log_{10}(S2/S1)$ distribution.

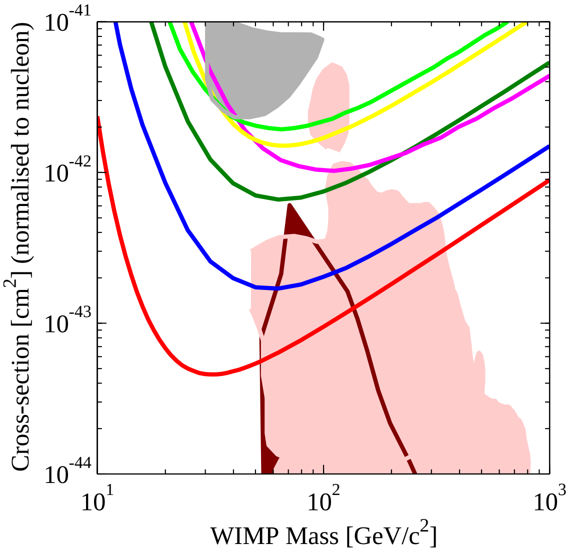

Figure 4. Spin-independent WIMP-nucleon cross-section upper limits (90% C.L.) versus WIMP mass. Limits from bottom to top: XENON10 (red) [10], CDMS II (cryogenic Ge/Si, blue) [11], Zeplin II (LXe, dark green) [12], WARP (LAr, magenta) [13], CRESST (cryogenic scintillator, yellow) [14], and KIMS (CsI, light green) [15]. The light gray area indicates the DAMA (NaI) annual modulation, if interpreted as DM signal [16]. The light and dark red areas are expectations for parameters in the constrained minimal supersymmetric models [2, 17].

cuts, including the energy window of 4.5 – 26.9 keV nuclear recoil equivalent energy and a fiducial volume corresponding to 5.4 kg detector mass. The selections were based on calibration data and an initial shorter background run. The detector was exposed for 58.6 live days during the period between October 6, 2006 and February 14, 2007, yielding a net exposure of 136 kg-days after all efficiencies. 10 Events were found in the search window where a gamma-ray background of 7 events was expected. The distribution of events in data space suggests a pure background origin of these events. Fig. 4 shows the XENON10 90% C.L. upper limit for spin-independent WIMP-nucleon cross-section per nucleon, which we derive using the "Maximum Gap" method [18]. The curve reaches a minimum value of $4.5 \times 10^{-44}\,\mathrm{cm}^2$ for a WIMP mass of 30 $\mathrm{GeV/cm}^2$ and is $8.8 \times 10^{-44}\,\mathrm{cm}^2$ for a WIMP mass of 100 GeV/c^2. See ref. [10] for details. Including other recent results, the figure also shows the impact of more recently applied liquid noble gas detector technology on spin-independent limits.

The next step in the XENON program, XENON100, is meanwhile underway at LNGS. XENON100 will be scaled up to 150 kg total, with an expected fiducial mass of 50 kg. With careful choices and screening of materials and an active LXe veto, XENON100 aims at testing DM interactions at a level 30 times lower than XENON10. With similar efforts (LUX) underway, prospects for 1 ton-scale LXe DM detectors in a 5 year time frame, and planned scale-ups of cryogenic and LAr detectors, as well as others, the prospects for WIMP Dark Matter search are very exciting indeed.

Acknowledgments

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