Recent results from the XENON100 experiment and future goals of the XENON project

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The XENON Dark Matter Program

2005 - 2007

2008-2015

2012-2017

XENON10
15 cm drift TPC - 25 kg

XENON100
30 cm drift TPC - 161 kg

XENON1T
100 cm drift TPC - 3300 kg
Direct detection: progress over time


~1 event kg⁻¹ day⁻¹
~1 event kg⁻¹ yr⁻¹

XENON10
XENON100
XENON1T
XENON1T Upgrade
Gran Sasso Underground Laboratory

1400m of rock
Muon flux reduced by $\sim 10^6$
$\sim 1$ muon/m²/hr
The XENON Collaboration

US led and NSF supported since start of project
~100 scientists from 15 institutions
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Liquid Xenon for a WIMP Detector

- Good target for both SI (A~131) and SD WIMP-N interactions ($^{129}$Xe & $^{131}$Xe)
- Highest event rate for massive WIMPs
- Unique ability to measure single $e^-$ with a two-phase TPC:
  - allows detection of light WIMPs through charge-channel only
- Enables large mass, homogeneous, self-shielded, easily scalable detector.
- Highest ionization and scintillation yield among all noble liquids
- Simultaneous charge and light detection enables ER/NR discrimination
- 3D event localization, double-scatter rejection and self-shielding provide powerful background rejection
- Excellent dielectric, inert, no long-lived radioactive isotopes.

![Graph showing event rate vs. recoil energy for different gases]

- 100 GeV, Ar
- 100 GeV, Ge
- 100 GeV, Xe
- 10 GeV, Xe
Two-phase Xe Time Projection Chamber

- Particle interaction in the active volume produces prompt scintillation (S1) and ionization electrons
- Electrons which reach the liquid/gas interface are extracted, accelerated in the gas gap and detected as proportional light (S2)
- PMTs in liquid and gas detect S1 and S2
- Charge/light depends on dE/dx: \((S2/S1)_{\text{WIMP}} \ll (S2/S1)_{\text{gamma}}\)
- 3D-position sensitive detector with particle ID

PMT array

Anode

Gate grid

drift field

Cathode

Calibration bands for particle ID

electron recoil

S2

S1

nuclear recoil

\(\gamma, \beta\)

\(n, \text{WIMP}\)
The XENON100 Experiment

TPC with 30 cm drift and 30 cm diameter

Drift field in LXe ~ 0.5 kV/cm

Amplification field in GXe ~10 kV/cm

161 kg Xe (62 kg as target; 99 kg as active veto)

Cooled with 200W PTR outside shield

Read-out with 242 PMTs with ~1 mBq (U/Th)

S1 yield: 2.3 pe/keV (@122 keV and 0.5 kV/cm)

S2 yield: 19 pe/e (single electron sensitive)

Kr/Xe level reduced to ppt with cryogenic distillation

Passive shielding: water/Pb/Poly/Cu

Event Localization in XENON100

Position reconstruction based on top S2 hit pattern

$\Delta r < 3 \text{ mm}$, $\Delta z < 0.3 \text{ mm}$, $\Delta z < 2 \text{ mm}$ for double-scatter separation
Energy Scale: from measured photoelectrons to keV

- Energy relation for $S_1$:
  
  \[ E = \frac{S_1}{L_y} \frac{1}{\mathcal{L}_{\text{eff}}(E)} \frac{S_{ee}}{S_{nr}}. \]

  - Light yield of 122keV $\gamma$-rays
  - Quenching-factor of nuclear recoils
  - Electric field dependency

- Energy relation for $S_2$:
  
  \[ E = \frac{S_2}{L_q} \frac{1}{Q_y(E)}. \]

  - Secondary Amplification of electron signals
  - Charge yield of nuclear recoils
XENON100 Response to Nuclear Recoils

\[ E = \frac{S_1}{L_y} \frac{1}{L_{\text{eff}}(E)} \frac{S_{ee}}{S_{nr}} \]

\[ E = \frac{S_2}{Y} \frac{1}{Q_y(E)} \]

Aprile et al. (XENON100) PRD 88, 012006 (2013)
Ongoing measurements of ERs and NRs in LXe to nail energy and field dependence down to a few keV

Similar apparatus and techniques (Compton scattering and nuclear scattering) used for the last measurement of $\text{Leff}$ and of the relative scintillation efficiency of ERs at zero field (Aprile et al. Phys. Rev. D 86 (2012). New detector (two-phase TPC with fine spatial resolution and high LY)

NeRiX Facility at Columbia
XENON100: an ultra-low background experiment

~5x 10^{-3} evts/kg/keV/day after veto cut and before S2/S1 discrimination

No Parameter tuning!

CoGeNT
Arxiv: 1002.4703

XE10 before fid.

CRESST
Arxiv: 0809.1829

XE10 after fid.

DAMA
Arxiv: 0912.3592

XE100 before fid.

CDMS
Arxiv: 0912.3592

XE100 after fid.

DAMA
Arxiv: 1002.1028

LUX before fid.

LUX before fid.

LUX after fid.

Enables powerful background suppression by volume fiducialization and event multiplicity

single scatter events after 225 live days of data taking 2011/2012: (trigger rate ~1Hz)

- 2 events observed with 1.0 ± 0.2 events expected
- 26.4% probability of upward background fluctuation
- No significant excess due to signal seen in XENON100 data
WIMP-like Event as seen in XENON100

3.6 PE detected (from \(~100\) S1 photons)

645 PE detected (from \(32\) ionization electrons which generated \(~3000\) S2 photons)
XENON100: Spin Independent/Dependent Limit

Aprile et al. (XENON100), Phys. Rev. Lett. 109 (2012)
XENON100: Spin Independent/Dependent Limit

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Light DM Search with XENON100 Data

- Search for MeV/GeV WIMPs using only S2 signal and annual modulation signature

  1-8 GeV WIMPs will give NRs with a few electrons which can be detected in XENON100 thanks to 100% trigger efficiency for events with >8 electrons (~20pe/e gain) [Aprile et al. PRL 109 (2012)]

  WIMPs with ~50 MeV can eject a few electrons of Xe atoms, detectable via S2 only analysis and the single-e detection ability of a two-phase TPC [Aprile et al. Phys.G: Nucl.Part.Phys. 41(2014)]

![Graph showing detection efficiency and trigger probability for S2 signal](image)

- Run I
- Run II
Axions and ALPs can interact with atomic electrons via the axioelectric effect producing ERs with energy equal to axion mass minus e-binding energy in Xe → solar axions (continuum spectrum) and galactic (monoenergetic) ALP.

The low background in XENON100 and its low ER threshold allows a very sensitive search. S1(PE) converted to keVee based on recent measurements of scintillation efficiency and its quenching with field by Columbia and UZH groups. 3PE threshold corresponds to 2 keVee.
XENON100 Still Taking Data

- 154 days of new DM data in 2013 (blinded) under analysis
- Combine with previous data for a more precise annual modulation search.
- Detector light yield enables search down to 2 keVee. Very stable performance
- Measured Kr/Xe < 1ppt level (demonstration for XENON1T)
- New neutron sources calibration (demonstration for XENON1T)
- We are currently modifying the shield to host the Y-Be source for low energy NR calibration
XENON1T
From XENON100 to XENON1T

- Two-phase TPC with 1 meter drift and ~1 m diameter electrodes exploiting ~3.3 tonnes of Xe
- Experiment designed to enable a fast upgrade to a larger diameter TPC exploiting ~7 tonnes of Xe
- Detector/associated systems use largely proven technologies developed for XENON100
- New challenges presented by the scale-up addressed with multiple R&D set-ups
- New 3 inch PMTs developed for XENON1T: average QE~40% at 178 nm and low activity
- Detector shielded by water implemented as Cherenkov muon veto
- Developing methods to control the most challenging backgrounds: from $^{85}\text{Kr}$ beta-decays (reduce Kr/Xe < 0.5 ppt) and from $^{214}\text{Pb}$ beta-decays (reduce $^{222}\text{Rn}$ in LXe to ~1 mBq/kg)
- Schedule: under construction at LNGS started fall 2013
- Science Goal: $2\times10^{-47}$ cm$^2$ with 2 ton-years of data or by 2017
- Funded with 50% of capital cost covered by NSF and the rest from Europe and Israel.
Science Reach of XENON1T Program

- 100 x more sensitive than XENON100 - 1000 x more after upgrade
- either exclude much of favored SUSY WIMPs parameter space
- ~100 events from a 50 GeV WIMP at $2 \times 10^{-47}$ cm$^2$ with 2 tonne-year
XENON1T Demonstrator at Columbia

To test technologies/inform design of XENON1T detector

1. cooling by Pulse Tube Refrigerator with efficient heat exchange

2. continuous purification of Xe with flow > 50 SLPM

3. demonstrate purity and HV with a 1 m-drift TPC
XENON1T Detector

3 m

1.6 m

24
XENON1T Detector

- 10 m high and 9.6 m diameter tank
- Lined with specular reflector
- 700 m$^3$ of pure water
- Cerenkov light detected with 84 x 8” PMTs
- $\mu$-induced neutron background: 0.01 per year $\ll$ WIMP signal
TPC details

Electrodes: 1 meter diameter wire grids
Field cage: Cu-rings; PTFE reflector
PMTs: 248 x 3” Hamamatsu R11410-21: ~40% QE @ 175 nm; <1mBq/PMT in U/Th
HV: 100kV custom-made feedthrough
TEP mock-up at LNGS
XENON1T Systems

- Cryogenic and Purification Room
- Electronics and DAQ Room
- ReStoX and Kr-Column Room
Xe Cryogenic & Purification

- under construction at Columbia and Munster
- commissioning at LNGS starts beginning of July
- Largely based on XENON100 and Demonstrator R&D
ResToX (fast recovery system) and Cryostat

- Double-walled, high pressure (70 atm), vacuum-insulated, LN2 cooled sphere
- Capable to store 7.6 tons of Xe either in gas or liquid/solid phase under high purity conditions
- It is aimed at recovering in a safe and controlled way LXe from detector.
- In case of emergency all LXe is recovered in a few hours

Cryostat under construction

- The outer vessel is capable to host an enlarged inner vessel to increase the active target from 3.3 to 7 tonnes.
Summary

- XENON100 is still in operation after 5yr. New DM data still blinded.
- New calibration sources will be tested also for XENON1T
- XENON1T construction is on schedule
- Commissioning of the cryostat and all cryogenic plants will start in July. We expect a full validation by end 2014. TPC will be installed by Spring 2015
- XNON1T data taking is expected by Summer 2015. After 2 ton-yr of data sensitivity reach is as shown
- An upgrade of XENON1T has been proposed to the NSF. Planned to start in 2018