Dark matter search with the XENON1T experiment

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On Behalf of the XENON Collaboration

Rencontres de Moriond,
Very High Energy Phenomena in the Universe,
La Thuile, 20/03/2017
Why do we look for dark matter?

Well motivated theoretical approach: **WIMP**

(Weakly Interacting Massive Particle)

- Predicted in theories beyond the standard model of particle physics
- Correct relic density for an annihilation rate $\sim$ weak scale

But dark matter could be non weakly-interacting or a completely different type of particle

- Gravitino, sterile neutrino, axion, superheavy WIMP . . .

$E_R \sim \mathcal{O}(10 \text{ keV})$
Liquid xenon as dark matter target

- Self-shielding from external radioactivity
  → High stopping power ($\rho_{\text{LXe}} \sim 3 \text{ g/cm}^3$)
- High ionisation & scintillation yields
- 178 nm UV photons
  → Direct detection with photosensor possible
- A few keV energy threshold achieved

- High atomic mass $A \sim 131$ → spin-independent interactions
- $^{129}\text{Xe}$ and $^{131}\text{Xe}$ → spin-dependent interactions
Two phase noble gas TPC

- Drift field
- Electronegative purity
- Position resolution

- Scintillation signal \((S1)\)
- Charges drift to the liquid-gas surface
- Proportional signal \((S2)\)

→ Electron- /nuclear recoil discrimination
Laboratori Nazionali del Gran Sasso (Italy) below 3650 m.w.e. shielding

- Completed: XENON100 with 62 kg active mass
- Currently taking data: XENON1T using 2 ton active mass
- Future: XENONnT with ~6 ton active mass
The XENON100 experiment

- Taking data from 2009 – 2016
- 30 cm drift length and 30 cm ∅
- 161 kg LXe mass (34 – 48 kg for analysis)
- Background $\sim 5 \cdot 10^{-3}$ events/(kg·d·keV)

Leading results during the last years
  - Spin independent result: PRL 109, 181301 (2012)
  - Spin dependent result: PRL 111, 021301 (2013)
  - Rate modulation: PRL 115, 091302 (2015)
    & update 2017: PRL 118, 101101 (2017)

...
Combined results from science runs I, II and III

477 live days (48 kg · year) acquired between (2010 – 2014)

Improved signal (in S1 and S2) and background modelling


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DAMA annual modulation

- Ultra radio-pure NaI crystals
- Annual modulation of the background rate in the energy region \((2 - 6)\) keV
- \(9.3 \sigma\) significance!


- No discrimination of electronic recoils from nuclear recoils

Data stability study

- Test of time modulation of electronic recoils of (2 – 6) keV energy
- Time span: 4 years (477 live days)
- DAMA signal excluded at 5.7 $\sigma$

XENON100, PRL 118, 101101 (2017) & arXiv:1701.00769
Goal: two orders of magnitude improvement in sensitivity with respect to XENON100
XENON1T infrastructure

- Kr-distillation column,
- purification & cryogenic systems,
- storage and filling systems, ...

→ All installed and commissioned early 2016
The XENON1T TPC

TPC design

~ 1 m height and 1 m ∅

2 t LXe in the target (3.2 t total mass)

Photosensors

248 low-background

Hamamatsu R11410 3-inch PMTs, EPJC 75 (2015) 11, 546
Low radioactivity sensor for XENON1T

- **High QE**: $\sim 35\%$ at 175 nm
- **30%** Single PE resolution
- **Sub-mBq** activities in U & Th

For reference: 1 Banana $\sim 15$ Bq in $^{40}$K

- **Low DC rates** in XENON1T:
  - $\langle R \rangle_{top} = 12$ Hz & $\langle R \rangle_{bottom} = 24$ Hz

PMT testing: JINST 12 P01024 (2017)
Background reduction

- **Nuclear recoil background**: in the WIMP signal region
- **Electronic recoil background**: affects signal region due to leakage

Example using calibration data from the XENON100 detector
Nuclear recoil backgrounds

- **External neutrons**: muon-induced, \((\alpha, n)\) & fission reactions
  - Underground location + active water Cherenkov veto
  - Material selection for low U and Th contaminations

- **Neutrinos**: Coherent neutrino-nucleus scattering

![Graph showing nuclear recoil energy vs rate](image)

**Graph details**:
- **Axes**:
  - X-axis: Nuclear Recoil Energy [keV]
  - Y-axis: NR Rate [kg⋅day⋅keV⁻¹]
  - **Curves**:
    - CNNS
    - Radiogenic neutrons
    - Muon-induced neutrons

**Equations**:
- **Muon veto design**, JINST 9 (2014) P11006
Electronic recoil backgrounds

- **External γ’s**: from natural radioactivity:
  - Suppression via self-shielding of the target
  - Material screening and selection
- **Neutrinos**: Elastic neutrino-electron scattering of $\nu$ from the Sun
- **Internal contamination**:
  - **Xenon**: $^{136}\text{Xe}$ $\beta\beta$ decay ($T_{1/2} = 2.3 \times 10^{21}$ y)
  - $^{85}\text{Kr}$: removal by cryogenic distillation
  - $\text{Rn}$: Material selection + eventually online removal

Average rate in the energy range (1 – 12) keV

XENON1T, JCAP04 (2016) 027, arXiv:1512.07501
Lowest background level of all LXe experiments

Krypton background reduced by online cryogenic distillation

Krypton level measured independently by RGMS


New and improved analysis software

Calibration campaign started in autumn 2016

Continuous data taking since then
Radon budget and its reduction

- Radon emanation measurements for material selection

![Miniatuized proportional counter](image)

Radon budget in XENON1T (preliminary)

- **R&D on radon reduction**
  - Surface cleaning/coating
  - Cryogenic distillation


- Prediction for XENON1T:
  
  \[10 \mu\text{Bq/kg}\]
Krypton distillation column operated in reverse mode without loss of xenon

Two distillation runs with & without a radon source

Reduction factor $R > 27$ at 95% C.L.

Analyzing Run0 data

- **Science data** acquired until the earthquake (Jan. 18th) being analysed
- Electronic recoil band determined from Rn220 calibration
- Nuclear recoil (signal region) data from AmBe neutron source
- Data corrections and processor performance tested on $^{83m}$Kr data
Calibration in large detectors

- Common $\gamma$-ray energies do not reach the inner volume
  $\rightarrow$ internal $^{220}\text{Rn}$ can be used
- Radon is injected from a $^{228}\text{Th}$ source
- Beta decay of $^{212}\text{Pb}$ used to define the background region
- No long lived isotopes in the $^{220}\text{Rn}$ chain $\rightarrow$ LXe doesn’t need to be purified
- Use of the source tested successfully in XENON100 and XENON1T

XENON100, arXiv:1611.03585
First XENON1T calibration data

- First calibration with $^{137}\text{Cs} \gamma$-source
- Spectrum derived using both light (S1) and charge (S2) signals
- Detector parameters (e.g. purity) have increased
  \[ \rightarrow \text{better resolution expected} \]

- Calibration with internal $^{83m}\text{Kr}$
- Low energy calibration lines at 32 keV and 9.4 keV
- **Light yield** is a factor of $2\times$ better than in XENON100
- Delay time between the lines consistent with literature values

\[ t_{1/2} = 156 \pm 1 \text{ ns (stat)} \]
XENON1T sensitivity

Figure updated from XENON1T, JCAP04(2016)027, arXiv:1512.07501

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Upgrade to XENONnT

- XENONnT will contain about 6 t LXe in the target
- All infrastructure built already to accommodate XENONnT
- ‘Only’ xenon, 230 new PMTs and new TPC necessary
- Background expectation: assuming negligible material BGs
  - ER BG: 0.13 ev/t/y (dominated by solar $\nu$’s)
  - NR BG: 0.23 ev/t/y (dominated by solar $\nu$’s)
- Sensitivity: $1.6 \times 10^{-48}$ cm$^2$ for 50 GeV/$c^2$ WIMP mass → for 20 t×y exposure

Currently > 8 t of LXe purchased and orders for the missing PMTs already placed
Summary

Sensitivity for dark matter searches has progressed rapidly

- Best sensitivities by liquid xenon detectors (above few GeV/c²)
- XENON1T currently taking data!
- XENONnT is the future device to investigate the dark matter properties and a wide variety of neutrino physics

DARWIN, JCAP 1611 (2016) no.11, 017, arXiv:1606.07001
Sensitivity evolution

Cross section $[\text{cm}^{-4}]$

- **Germanium detector**
- **Cryogenic bolometer**
- **Liquid xenon detector**
- **Liquid argon detector**

Neutrino background

Spin-independent interactions: coupling to nuclear mass

\[ \sigma_{SI} = \frac{m_N^2}{4\pi(m_\chi + m_N)^2} \cdot \left[ Z \cdot f_p + (A - Z) \cdot f_n \right]^2 \]

\( f_{p,n} \): effective couplings to p and n.

Spin-dependent interactions: coupling to nuclear spin

\[ \sigma_{SD} = \frac{32}{\pi} \cdot G_F \cdot \frac{m_\chi^2 m_N^2}{(m_\chi + m_N)^2} \cdot \frac{J_{N+1}}{J_N} \cdot \left[ a_p \langle S_p \rangle + a_n \langle S_n \rangle \right]^2 \]

\( \langle S_{p,n} \rangle \): expectation of the spin content of the p, n in the target nuclei

\( a_{p,n} \): effective couplings to p and n.
XENON1T sensitivity evolution

Figure updated from XENON1T, JCAP04 (2016) 027, arXiv:1512.07501

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La Thuile, 20/03/2017
DARWIN: the ultimate WIMP detector

- R&D and design study for a liquid xenon observatory
- Design phase on-going, followed by construction and commissioning
- TPC of $\sim 2.6$ m diameter & $2.6$ m drift length
- 7 years necessary to exploit the complete sensitivity
- Location: possibly inside the XENON1T/nT water tank

http://darwin-observatory.org/
50 t LXe total (40 t in the TPC)