New results from the XENON10 direct dark matter search

Dan McKinsey

Yale University Physics Department

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Searching for WIMPs

**Accelerators:** Look for dark matter candidates at the LHC (lifetime limit < 1 ms)

**Indirect Searches:** Look for $\overline{\nu} \nu$ annihilation in form of high energy cosmics, neutrinos

**Direct Searches:**

$$R = N \overline{\nu} \nu <v>$$

From $<v> = 220 \text{ km/s}$, get order of 10 keV deposited per nuclear recoil event

**Key technical challenges:**
- Low radioactivity
- Low energy threshold
- Gamma ray rejection
- Scalability

Detect heat, light, or ionization
(or some combination)

Germanium detector (as in CDMS, Edelweiss)
Some standard radiation detectors

- Geiger counter
- Sodium iodide crystal
- Germanium

Gamma ray interaction rate is proportional to $(\# \text{ of electrons in detector}) \times (\text{gamma ray flux})$

Typical count rate $= 100 \text{ events/second/kg} = 10,000,000 \text{ events/day/kg}$

Put it in a good lead shield ---> rate drops to 100 events/day/kg.

State-of-the-art dark matter detectors ---> sensitive to 0.01 events/kg/day
The Noble Liquid Revolution

Noble liquids are relatively inexpensive, easy to obtain, and dense.

Easily purified
- low reactivity
- impurities freeze out
- low surface binding
- purification easiest for lighter noble liquids

Ionization electrons may be drifted through the heavier noble liquids

Very high scintillation yields
- noble liquids do not absorb their own scintillation
- 30,000 to 40,000 photons/MeV
- modest quenching factors for nuclear recoils

Easy construction of large, homogeneous detectors
## Liquified Noble Gases: Basic Properties

Dense and homogeneous  
Do not attach electrons, heavier noble gases give high electron mobility  
Easy to purify (especially lighter noble gases)  
Inert, not flammable, very good dielectrics  
Bright scintillators

<table>
<thead>
<tr>
<th></th>
<th>Liquid density (g/cc)</th>
<th>Boiling point at 1 bar (K)</th>
<th>Electron mobility (cm²/Vs)</th>
<th>Scintillation wavelength (nm)</th>
<th>Scintillation yield (photons/MeV)</th>
<th>Long-lived radioactive isotopes</th>
<th>Triplet molecule lifetime (µs)</th>
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</thead>
<tbody>
<tr>
<td>LHe</td>
<td>0.145</td>
<td>4.2</td>
<td>low</td>
<td>80</td>
<td>19,000</td>
<td>none</td>
<td>13,000,000</td>
</tr>
<tr>
<td>LNe</td>
<td>1.2</td>
<td>27.1</td>
<td>low</td>
<td>78</td>
<td>30,000</td>
<td>none</td>
<td>15</td>
</tr>
<tr>
<td>LAr</td>
<td>1.4</td>
<td>87.3</td>
<td>400</td>
<td>125</td>
<td>40,000</td>
<td>³⁹Ar, ⁴²Ar</td>
<td>1.6</td>
</tr>
<tr>
<td>LKr</td>
<td>2.4</td>
<td>120</td>
<td>1200</td>
<td>150</td>
<td>25,000</td>
<td>⁸¹Kr, ⁸⁵Kr</td>
<td>0.09</td>
</tr>
<tr>
<td>LXe</td>
<td>3.0</td>
<td>165</td>
<td>2200</td>
<td>175</td>
<td>42,000</td>
<td>¹³⁶Xe</td>
<td>0.03</td>
</tr>
</tbody>
</table>
100 GeV WIMP \( \sigma_p = 10^{-44} \text{ cm}^2 \)

- Blue line: Ar
- Green line: Ne
- Red line: Xe

Event rate (kg/day/keV) vs. Nuclear recoil energy (keV)
Strategies for Electronic Recoil Background Reduction in Scintillation Experiments

Require < 1 event in signal band during WIMP search

LXe: Self-shielding, Ionization/Scintillation ratio best
LAr: Pulse shape, Ionization/Scintillation ratio best
LNe: Pulse shape, Self-shielding best
The XENON10 Collaboration

Columbia University  Elena Aprile, Karl-Ludwig Giboni, Maria Elena Monzani, Guillaume Plante, Roberto Santorelli, and Masaki Yamashita
Brown University  Richard Gaitskell, Simon Fiorucci, Peter Sorenson, and Luiz DeVvieiros
RWTH Aachen University  Laura Baudis, Jesse Angle, Joerg Orboeck, Aaron Manalaysay, and Stephen Schulte
Lawrence Livermore National Laboratory  Adam Bernstein, Chris Hagmann, Norm Madden, and Celeste Winant
Case Western Reserve University  Tom Shutt, Peter Brusov, Eric Dahl, John Kwong, and Alex Bolozdynya
Rice University  Uwe Oberlack, Roman Gomez, Christopher Olson, and Peter Shagin
Yale University  Daniel McKinsey, Richard Hasty, Louis Kastens, Angel Manzur, and Kaixuan Ni
Coimbra University  Jose Matias Lopes, Luis Coelho, Luis Fernandes, and Joaquim Santos

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The XENON Detector: How It Works

- **WIMP or Neutron**
- **Gamma or Electron**
- **Bottom PMT Array**
- **PMT Array**
- **Proportional Gas Xe**
- **Liquid Xe**

- **S1**
- **S2**
- **(S2/S1)_{\text{WIMP}} \ll (S2/S1)_{\text{gamma}}**

- **Nuclear Recoil**
- **Electron Recoil**
LXe cell at Yale

used for level meter development, LXe scintillation for nuclear recoils, PMT testing in LXe, GEM testing
LXe level meters

- LXe level meters
- 20 cm dynamic range
- 20 micron sensitivity

![LXe level meter image]

Graph:
- Scintillation cell
- Liquefaction cell
- Level Meter
- Liquid % vs. Time (hours)
The XENON10 Detector

- Pulse tube cryocooler
- Vacuum Cryostat
- Re-condenser
- TPC active area ~ 20 cm diameter; drift gap = 15 cm
- Filled with 22 kg (15 kg active) of ultra pure LXe commercially purified to < 10 ppb Kr-85 ~ 200 μdru
- High Purity (> 2 ms electron lifetime) achieved with continuous gas circulation through hot getter
- Custom designed HV feedthrough for low radioactivity (700 V/cm drift field with good uniformity)
- SS vessel and vacuum cryostat
- 89 PMTs (R8520-06-AL): 48 in GXe and 41 in LXe
- Gain Calibration by blue LED mounted in detector
- Light response (S1): 2.25 pe/keV at 662 keV; 3.0 pe/keV at 122 keV (with field) → 5 keV threshold achieved
- X-Y position from PMTs hit pattern; \( \sigma_{x-y} \approx 2 \) mm
- Z-position from \( \Delta t_{\text{drift}} \) (\( v_{d,e} \approx 2 \) mm/\( \mu s \)), \( \sigma_z \approx 1 \) mm
- Pulse Tube refrigerator for stable operation at –95°C
- Optical and Mass Models with GEANT4 MC
The XENON10 Photomultipliers
Hamamatsu 8520-06-AL 2.5 cm x 3.5 cm
Bialkali photocathode Rb-Cs-Sb
10 dynodes
Quartz window
U/Th/K/Co = 0.17/0.20/0.09/0.56 mBq/PMT
Quantum efficiency > 20% at 178 nm

Angel Manzur (Yale) individually testing PMTs
The INFN Gran Sasso National Lab (LNGS)

Muon flux vs overburden

- Turin
- Florence
- Gran Sasso
- Rome
- Naples
- Soudan
- Kamioka
- Gran Sasso (CDMS II)
- Homestake (Chlorine)
- Baksan
- Mont Blanc
- Sudbury
- WIPP
- NUSL - Homestake

1400 m rock overburden (3500 mwe)
XENON10 teams begin work at Gran Sasso, spring 2006

Offices and above-ground laboratories at Gran Sasso

Yalies at Gran Sasso, 7/2006:
Angel Manzur (grad student),
Ruth Toner (undergrad),
Kaixuan Ni (postdoc)
XENON Slow Control System (Yale)

- Developed in Java using Java RMI for remote interface.
- Platform Independent.
- Monitors ~330 channels.
- Remote high voltage control.
- Scalable to more instruments or computers.

**Diagram: XeSCS System Components**

- **Xe Pressures**
- **Cryogenic Temperatures**
- **Level Meters**
- **High Voltages & Currents**
- **Flow Meter**
- **Cryostat Vacuum**
- **Room Temperatures**
- **Inclinometer**
- **XeSCS computer**
- **XeSCS server**
- **Webpage** (monitor only)
- **Alarm computer @ Yale**
- **XeSCS clients** (monitor & control)
- **Mobile phone messages**
- **Status & alarm e-mails**

**Locations:***
- Underground LNGS
- Above ground LNGS
- Outside World

**Tech Details:**
- Developed in Java using Java RMI for remote interface.
- Platform Independent.
- Monitors ~330 channels.
- Remote high voltage control.
- Scalable to more instruments or computers.
Louis Kastens and Angel Manzur (Yale grad students) and XENON10
XENON10 Live-Time / Dark Matter Run Stability

XENON10 -- Running Days vs. Live-Days

- Unblinded
- Blind
- Neutron (x10)

Blind WIMP Search Data + Periodic Calib 92% Live

XENON10 Calibration runs @ LNGS

Time Integrated S1 Signals

Time Integrated S2 Signals

S1 Signal (Separate Signals in PMTs)

S1 and S2 Signal (Red - Σ Top PMTs, Blue - Σ Bottom PMTs)
AmBe source

- AmBe source. 3.7 MBq (220 n/sec) $\pm 15\%$
- 5 cm of lead between the detector and the source to stop the $\gamma$
- 12 hour run at trigger rate $\sim 14$ Hz


Neutron spectrum
\[ E_{nr} = \frac{S_1}{L_y L_{eff} S_{nr}} \]
Energy Calibration: determine the energy of nuclear recoils

Energy of nuclear recoils (NRs)

\[ E_{nr} = \frac{S_1}{L_y/L_{eff}} \cdot \frac{S_{er}}{S_{nr}} \]

Relative scintillation efficiency of NRs to 122 keV γ's at zero field

Quenching of scintillation yield for 122 keV γ's due to drift field

Quenching of scintillation yield for NRs due to drift field

Measured signal in # of pe

Light yield for 122 keV γ in \( \text{pe/keVee} \)

122 keV γ (Co-57)
Xenon Activation with Cf-252 at Yale

measure the scintillation light in a liquid Xenon cell

continuous activating Xe gas with a $5 \times 10^5$ n/sec Cf-252 source for 12 days
Xenon Activation with Cf-252

continuous activating Xe gas with a $5 \times 10^5$ n/sec Cf-252 source for 12 days

after 12-days of activation...

- Xe-131: 164 keV (200 Bq/kg)
- Xe-129: 236 keV (270 Bq/kg)
- Xe-133:

Counts/keV/kg/sec

Energy [keVee]
Xenon Activation with Cf-252

Yale (USA)

XENON10
Gran Sasso (Italy)

~ 1 week
Neutron-activated xenon added to XENON10
Activated Xenon Lines in XENON10

- Xe-131: 164 keV
- Xe-129: 236 keV
Position dependence of S1 signals in XENON10 after position-dependent corrections
Position dependence of S1 and S2 signals

The XENON10 results are from position-dependent corrected signals by using these maps obtained from activated-Xe calibration.
Fiducial Volume chosen by both Analyses:

15 < dt < 65 us, r < 80 mm

Fiducial Mass = 5.4 kg (reconstructed radius is algorithm dependent)

Overall Background in Fiducial Volume ~0.6 event/(kg d keVee)
**XENON10 Gamma/Neutron calibration**

### Neutrons
- **ER-Centroid**
- **NR-Centroid**

### Gammas
- **ER-Centroid**
- **NR-Centroid**

**AmBe Neutron Calibration (NR-band)**

**Cs-137 Gamma Calibration (ER-band)**

![Graphs showing neutron and gamma calibration](image-url)
Gamma background rejection efficiency

~ 99.5 % rejection power (improves to 99.9 % at low energy) at 50% Nuclear Recoil Acceptance
136 kg-days Exposure = 58.6 live days x 5.4 kg x 0.86 (ε) x 0.50 (50% NR)

WIMP Search Data

~1800 events

- WIMP “Box” defined at ~50% acceptance of Nuclear Recoils (blue lines): [Mean, -3σ]
- 10 events in the “box” after all cuts in Primary Analysis
- 6.9 statistical leakage events expected from ER band
- NR energy scale based on 19% constant QF

XENON10 WIMP Search Data
New XENON10 WIMP dark matter limit, announced at April APS meeting


Limit shown does not take into account any background subtraction
Other XENON10 papers in progress:

1) Spin-dependent limits

2) Detailed paper on the detector

3) Nuclear recoil response of XENON10

4) Radioactive backgrounds in XENON10

watch for arXiv submissions in coming 2 months...
Summary

1) Noble liquids (LXe, LAr, LNe) are promising for WIMP direct detection experiments, primarily because of their scalability.

2) The XENON10 experiment has recently performed the most sensitive WIMP search to date, with a 90% C.L. limit of 8.8E-44 cm^2 at 100 GeV.

3) Future two-phase experiments with liquid Xe are likely to make rapid advances in testing even lower WIMP-nucleon cross-sections (see LUX talk by M.Tripathi, next!)