The LUX Dark Matter Experiment

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TAUP 2009, Rome
350 kg Dual Phase Liquid Xenon Time Projection Chamber, fully funded by NSF and DOE
2 kV/cm drift field in liquid, 5 kV/cm for extraction, and 10 kV/cm in gas phase.
122 PMTs (Hamamatsu R8778) in two arrays
3D imaging via TPC eliminates surface events, defines 100 kg fiducial mass
The LUX-350 Collaboration

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Yale University: Susie Bedikian, Sidney Cahn, Alessandro Curioni, Louis Kastens, Alexey Lyashenko, Daniel McKinsey, James Nikkel
LXe is a good self-shielding material, with a scattering length of 6 cm at 1 MeV.

X-rays in the energy window of interest (5–25 keVr, or 1.3–8 keVee), are absorbed in less than a mm. Background is then dominated by higher energy gamma rays that penetrate the fiducial volume, scatter, and escape.

By defining a fiducial volume, gamma ray backgrounds drop enormously, scaling as $\exp[-L/L_s]$, where $L$ is the size of the active volume, and $L_s$ is the gamma ray scattering length.

In LUX, the dominant gamma ray background comes from the PMTs. Simulations assume high end of measurements: $U/Th/K/Co = 18/17/30/8$ (mBq/PMT)

This gives $8.3 \times 10^{-4}$ events/keVee/kg/day in the 100 kg fiducial mass. After discrimination cut, assuming a conservative efficiency of 99.4%, this gives $4.6 \times 10^{-6}$ events/keVee/kg/day, or 1 background event in 30,000 kg days.

above: Monte Carlo of (dominant) PMT activity in LUX
Other (subdominant) gamma ray backgrounds

Cryostat: We are building a low-background titanium cryostat, with material we have measured to have superior background characteristics. Background rates have been measured to be < a few mBq/kg in U, Th, K.

PTFE: Bulk PTFE can be purchased extremely radiopure; EXO measures U/Th/K < 0.004/<0.001/0.053 mBq/kg [1] in PTFE pellets. Heusser measures < 0.16/< 0.16/0.7 mBq/kg [2] in PTFE samples, which would give only 6E-8 events/keVee/kg/day after discrimination, or only 1.2% of the maximum expected background level from the PMTs.

[2] G. Heusser, M. Laubensteinb, H. Nederab, Low-level germanium gamma-ray spectrometry at the μBq/kg level and future developments towards higher sensitivity
<table>
<thead>
<tr>
<th>Sample Type</th>
<th>Grade</th>
<th>Dim.</th>
<th># of piece</th>
<th>Total weight</th>
<th>Counted At</th>
<th>U (ppb)</th>
<th>mBq/kg</th>
<th>Th (ppb)</th>
<th>mBq/kg</th>
<th>K-40 (ppm)</th>
<th>mBq/kg</th>
<th>Sc-46 (mBq/kg)</th>
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</thead>
<tbody>
<tr>
<td>Ti1</td>
<td>3/8&quot; plate</td>
<td>CP1</td>
<td>2.5&quot; x 6&quot;</td>
<td>4</td>
<td>1.87 kg</td>
<td>Oroville</td>
<td>&lt;0.2</td>
<td>&lt;2.5</td>
<td>&lt;0.4</td>
<td>&lt;1.6</td>
<td>&lt;0.2</td>
<td>&lt;6.2</td>
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<tr>
<td>Ti2</td>
<td>3/16&quot; plate</td>
<td>CP2</td>
<td>4&quot; x 6&quot;</td>
<td>20</td>
<td>7.55 kg</td>
<td>SOLO</td>
<td>10.4</td>
<td>130</td>
<td>17.5</td>
<td>70</td>
<td>--</td>
<td></td>
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<tr>
<td>Ti3</td>
<td>0.358&quot; plate</td>
<td>CP2</td>
<td>~ 1.3&quot; x 6&quot;</td>
<td>8</td>
<td>1.55 kg</td>
<td>SOLO</td>
<td>85</td>
<td></td>
<td>35</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Ti6</td>
<td>3/16&quot; plate</td>
<td>CP1</td>
<td>4&quot; x 6&quot;</td>
<td>20</td>
<td>7.98 kg</td>
<td>Oroville</td>
<td>&lt;0.03</td>
<td>&lt;0.4</td>
<td>&lt;0.2</td>
<td>&lt;0.8</td>
<td>&lt;0.05</td>
<td>&lt;1.6</td>
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<td>Ti7</td>
<td>1&quot; plate</td>
<td>CP1</td>
<td>2&quot; x 6&quot;</td>
<td>8</td>
<td>7.201 kg</td>
<td>Oroville</td>
<td>&lt;0.02</td>
<td>&lt;0.05</td>
<td>&lt;0.04</td>
<td>&lt;2.5</td>
<td></td>
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<td>Ti8</td>
<td>0.063&quot; sheet</td>
<td>CP1</td>
<td>4&quot; x 6&quot;</td>
<td>40</td>
<td>4.399 kg</td>
<td>Oroville</td>
<td>&lt;0.1</td>
<td>&lt;0.4</td>
<td>&lt;0.3</td>
<td>6</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Sample activated in air transport.
Not a problem for construction.
Materials. 86 days half-life.
Fast neutron backgrounds from bulk materials in LUX

PMTs are the dominant source of fast neutron background:
- fission neutrons negligible (1.5% of goal)
- \((\alpha, n)\) reactions on light elements dominate

Assuming U/Th/K/Co = 18/17/30/8 mBq/PMT,

=> 1.5 neutrons/yr/PMT

If the U/Th activity is confined entirely to the PMT glass stem and other glasses and insulators, this comes to 5 n/PMT/year.

After a multiple scattering cut, 5 n/PMT/yr results in a nuclear recoil background well below the goal of 5E-6 events/keVr/kg/day.

\((\alpha, n)\) reactions in PTFE are subdominant (8/year) assuming Heusser U/Th measurements. (Even lower assuming EXO numbers).

multiple scatter veto for neutrons!
Water Shield

2.5 meters of instrumented water shielding

Gamma rays from rock contribute < 2% of total electronic recoil background.

Fast neutrons from rock are moderated and captured extremely efficiently => negligible.

Muon-induced neutrons in rock: < 0.01 events/year in detector.
Internal Backgrounds

Kr-85: Beta decay, 687 keV endpoint. Normally at ppm in commercial Xe, though can purchase at 5 ppb. LUX requirement is 5 parts per trillion. Achieved by charcoal column separation (\(< 2\) ppt demonstrated at Case).

\(^{14}\)C, T, U, Th: Removed efficiently by getter.

Radon: Pb-210 daughter removed by getter. Surface daughter backgrounds removed by fiducial cut. Pb-214 makes a "naked" beta, which sets the LUX requirement = 16 mBq, compared to XENON10 measured rate of 1.6 mBq.

pp \(\nu\)'s: Elastic scattering of neutrinos from electrons gives background of 6E-8 events/keVee/kg/day, after discrimination.

Xe-136: Double beta decay background of 1.5E-8 events/keVee/kg/day, assuming \(\tau_{1/2} = 0.8 \times 10^{22}\) years (current lower limit).

Chemically active cosmogenic activation products removed by getter.

Xe-131m, Xe-129m decay away with \(\sim 10\) days half-lives.
Circulation and Purification System

Gas-phase purification using SAES getter
Demonstrated flow rate of 50 standard liters per minute

Gas panels

Circulation pump
Surface Facility at Homestake

LUX integration planned for October 2009
The Davis Cavern
Dewatering Milestone

Photomultiplier R&D

New 3'' PMTs -- Hamamatsu R11065

With 2x collection area of R8778

Background target for U/Th of 1/1 mBq

Single photoelectron resolution obtained from first articles of Hamamatsu
Experimental setup

\[ E_R = E_n \frac{2m_n M_{Xe}}{(m_n + M_{Xe})^2} (1 - \cos \theta) \]

Energies: 4 - 66 keVr
Results

- No significant dependence on field.
- The Leff decreases with decreasing energy.
- Escape electrons seem to be an important contributor to Leff.
\[ \mathcal{L}_{\text{eff}} \] model

\[ \mathcal{L}_{\text{eff}} = q_{\text{ncl}} \times q_{\text{el}} \times q_{\text{esc}} \]

- \( q_{\text{ncl}} \) nuclear quenching (Lindhard factor), energy goes into heat.
- \( q_{\text{el}} \) electronic quenching. Bi-excitonic collisions

\[ \text{Xe}^* + \text{Xe}^* \rightarrow \text{Xe} + \text{Xe}^+ + e^- \]

\[ q_{el} = \frac{1}{1 + k \frac{dE}{dx}} \]

- Escape electrons

\[ q_{esc} = \frac{N_{\text{ex}} + N_i - N_{\text{esc}}}{N_{\text{ex}}^{122} + N_i^{122} - N_{\text{esc}}^{122}} = \frac{\alpha + 1 - \beta}{\alpha + 1 - \beta^{122}} \]
$\mathcal{L}_{eff}$ model

Graph

Relative Scintillation Efficiency

Energy [keVr]

$\text{Lindhard } q_{ncl}$

$q_{ncl} \times q_{ol}$

$\text{Leff } = q_{ncl} \times q_{el} \times q_{esc}$
XENON10 limit

\[ \sigma_{\text{WIMP-nucleon}} \left[ \text{cm}^2 \right] \]

- \( \sigma_{\text{WIMP-nucleon}} = 10^{-41} \) at \( m = 10 \text{ GeV} \)
- \( \sigma_{\text{WIMP-nucleon}} = 10^{-42} \) at \( m = 100 \text{ GeV} \)
- \( \sigma_{\text{WIMP-nucleon}} = 10^{-43} \) at \( m = 1000 \text{ GeV} \)

Leff = 0.19
Leff model

Mass [GeV]

10
100
1000
Kr-83m calibration source development at Yale

Rb-83 purchased in aqueous solution, then coated on zeolite. Continually emits Kr-83m, which can then be used to calibrate the liquid xenon detector response.

\[ ^{83}\text{Rb} \quad 86.2 \text{ days} \]

62% 31%

521 keV 530 keV
46% 31%

32.1 keV 1.86 hours
9.4 keV 155 nsec

Rb-83 adsorbed on zeolite beads, in vacuum plumbing
LXe scintillation data from Kr-83m dissolved into LXe

L. Kastens et al, arXiv:0905.1766
The LZ3 and LZ20 Collaboration

Merger with ZEPLIN-III collaboration. Plus, some new US groups joining in. New members:

A. Murphy, C. Ghag, E. Barnes, A. Hollingsworth, P. Scovell
*Edinburgh University, United Kingdom*

*Imperial College London, United Kingdom*

N. Smith, G. Kalmus, P. Smith, P. Majewski, B. Edwards
*STFC Rutherford Appleton Lab, United Kingdom*

I. Lopes, V. Chepel, J. Pinto da Cunha, F. Neves, A. Lindote, V. Solovov, C. Silva
*LIP - Coimbra, Portugal*

D. Akimov, V. Belov, A. Burenkov, A. Kobyakin, A. Kolvalenko, V. Stekanov
*ITEP - Moscow, Russia*

J. Siegrist
*Lawrence Berkeley National Laboratory*

H. Nelson
*University of California, Santa Barbara*
Long Term Program

![Graph showing cross-section vs. WIMP mass](http://dmtools.brown.edu/Gaitskell,Mandic,Filippini)

- LUX-350 (2008-2010)
- LUX-ZEPLIN 3 tonnes (2010-2013)
Extra Slides
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>
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<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>
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<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>
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<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>
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<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 \( \sigma_p = 10^{-44} \text{ cm}^2 \)

![Graph showing event rate vs. nuclear recoil energy for 100 GeV WIMP detection with different target gases: Ar (blue), Ne (green), Xe (red).](image-url)
XENON10 measured discrimination power

~ 99.5% electron recoil rejection (improves to 99.9% at low energy (50% nuclear recoil acceptance).
Selecting single nuclear recoils

- Quality cuts $Q_0$: remove noise event, high energy events, $S_1$ asymmetry
- Select neutrons using PSD and time of flight (TOF)
Systematic error

- a) Multiple elastic scatters
- b) Outside scatters
- c) Size and position
- d) Cross-section database
  \(~2 - 4\%\)
To compare MC & data:

1. $E_R \rightarrow E_e$
2. $\sigma = 3.2 \sqrt{N_{phe}}$
3. software + trigger efficiency