LUX: A Liquid Xenon Dark Matter Detector

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KEK Physics Seminar

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1. Water Shield
2. Thermosyphon
3. Xenon recirculation and heat exchanger
4. Feedthroughs
5. Photomultiplier Tubes
6. Time Projection Chamber

- 350 kg liquid xenon
- Cathode
- Anode and electron extraction grids
- Inner Titanium cryostat
- Superinsulation
- Titanium cryostat

Ultra-low radioactivity inner and outer titanium cryostats. The inner cryostat is covered by a copper radiation shield (left). The inner cryostat contains the liquid xenon, grids and PMTs. The vacuum separation between the outer and inner cryostat, in addition to the superinsulation (middle figure), prevent the detector (which is at about 170 K) from warming up.

In addition to liquid xenon's self-shielding, the 8-meter diameter by 6-meter height reduces gamma background by 10 orders of magnitude.

Closed loop of liquid nitrogen condensation/evaporation. Provides 1 kW cooling power to the detector.

Xenon is constantly being recirculated in and out of the detector for purification. The heat exchanger transfers the heat load from the incoming xenon gas to the outgoing xenon liquid.

The PMT hit pattern provides x-y localization of an event, while the time between primary (S1) and secondary (S2) scintillation signals provides z-localization.
Evidences of Dark Matter

Original claim was made by Fritz Zwicky (1933)

- Measured line-of-sight velocities of the galaxies in the Coma cluster
- Inferred the total mass of the cluster to be 100x larger than that of the luminous matter component
- Explanation: substantial amount of non-luminous matter must exist
Rotational Curve

Vera Rubin et al. (1979) measured orbital velocity vs. radius of spiral galaxies

- If the mass distribution $\approx$ luminosity distribution, i.e. concentrated at the center, $v(r)$ should drop as $\frac{1}{\sqrt{r}}$ at large $r$

Observation disagrees

- Large amount of matter (which does not emit light) is distributed far away from the center
Bullet Cluster

Two colliding clusters of galaxies are observed in three ways:

- Optical telescope sees the stars
- X-ray sees hot interstellar gases (shown in red)
- Gravitational lensing sees the mass distribution (shown in blue)

Different components suffer different effects in the collision

- Hot gases interact electromagnetically, and thus strongly decelerated
- Stars suffer smaller disturbances
- Mass dist. appears to pass through without being disturbed
Existence of Dark Matter is established from its gravitational effects.

Amount of Dark Matter is inferred from astronomical data:
- ~23% of the energy of the Universe
- Local density 0.3 GeV/cm³

Identity of Dark Matter is unknown:
- Majority must be cold (i.e. non-relativistic) and non-baryonic
- They are not a part of the Standard Model

Dark Matter is a particle physics problem as much as it is an astronomy problem.
WIMP Dark Matter

No shortage of candidates, but...

WIMPs (Weakly Interacting Massive Particles) are the front runners

- ~100 GeV new particles with Weak (and gravitational) interactions
- Such a particle would naturally have the right thermal relic density

Many theories beyond the SM predict WIMPs

- Attempting to solve the hierarchy problem often results in new stable particles at the Weak scale
- Example: SUSY with R-parity and the Lightest Supersymmetric Particle
WIMP Hunting

Going beyond gravity, three ways to detect WIMPs

- WIMP pair production at the hadron colliders

\[ \sigma(ff \rightarrow \chi\bar{\chi}) \]

- Observe radiation from WIMP pair annihilation

\[ \sigma(\chi\bar{\chi} \rightarrow ff) \]

- Direct detection: WIMP scattering off a nucleus in the detector

\[ \sigma(\chi f \rightarrow \chi f) \]

Cross sections are related, and constrained by the relic abundance

- Predictions are model dependent
Direct Detection Limits

Best limits on the WIMP-nucleon cross section are \( \sim 4 \times 10^{-44} \text{ cm}^2 \)

- CDMS II: Ge (and Si) crystals at 10 mK, 612 kg-day exposure
  \( \Rightarrow < 3.8 \times 10^{-44} \text{ cm}^2 \) at 70 GeV
- XENON10: liquid Xe, 316 kg-day
  \( \Rightarrow < 5.6 \times 10^{-44} \text{ cm}^2 \) at 30 GeV

SUSY models predict the cross sections around \( 10^{-44} \text{ cm}^2 \)

- Smaller cross sections are possible, but less favored by other particle-physics experimental data

Next generation of experiments are aiming for \( \sigma_{\chi N} \sim 10^{-45} \text{ cm}^2 \)
CDMS II Events

FIG. 2: Ionization yield versus recoil energy for events passing all cuts, excluding yield and timing. The top/bottom plot shows events for detector T1Z5/T3Z4. The solid red lines indicate the 2\textsuperscript{electron} and nuclear recoil bands. The vertical dashed line represents the recoil energy threshold and the sloping magenta dashed line is the ionization threshold. Events that pass the timing cut are shown with round markers. The candidate events are the round markers inside the nuclear-recoil bands. \textit{Color online.}

Such events are more prevalent in WIMPH search data than in the data sets used to generate the preblinding estimate of misidentified surface events. A refined calculation, which accounts for this reconstruction degradation, produced a revised surface event estimate of \(k_{\text{stat}} \pm k_{\text{mcsyst}}\). The systematic uncertainty is dominated by our assumption that the pass/fail ratio for multiple scatter events is the same as that for single scatter events. Based on this revised estimate, the probability to have observed two or more surface events in this exposure is \(k_{\text{inclusion}}\) of the neutron background estimate increases this probability to \(k_{\text{ni}}\). These expectations indicate that the results of this analysis cannot be interpreted as significant evidence for WIMP interactions but we cannot reject either event as significant.

To quantify the proximity of these events to the surface event rejection threshold, we varied the timing cut threshold of the analysis. Reducing the revised expected surface event background to \(k_{\text{obs}}\) events would remove both candidates while reducing the WIMP exposure by \(s\). No additional events would be added to

FIG. 3: Normalized ionization yield (number of standard deviations from mean of nuclear recoil band) versus normalized timing parameter (timing relative to acceptance region) for events passing all cuts, excluding yield and timing. The top/bottom plot shows events for detector T1Z5/T3Z4. Events that pass the phonon timing cut are shown with round markers. The solid red box indicates the signal region for that detector. The candidate events are the round markers inside the signal regions. \textit{Color online.}

the signal region until we increased the revised estimate of the expected surface event background to \(l_{\text{inclusion}}\) events. We calculate an upper limit on the WIMP-nucleon elastic scattering cross section based on standard galactic halo assumptions \(l_{\text{kl}}\) and in the presence of two events at the observed energies. We use the Optimum Interval Method \(l_{\text{ml}}\) with no background subtraction. The resulting limit shown in Fig. o has a minimum cross section of \(r_44\) cm\(^2\) when combined with our previous results \(l_{\text{ll}}\) for a WIMP of mass \(r_{\text{GeV}}\). The abrupt feature near the minimum of the new limit curve is a consequence of a threshold crossing at which intervals containing one event enter into the optimum interval computation \(l_{\text{ml}}\). An improved estimate of our detector masses was used for the exposure calculation of the present work. A similar correction resulting in a decrease in exposure was applied to our previous CDMS result \(l_{\text{ll}}\) shown in Fig. o. While this work represents a doubling of previously analyzed exposure, the observation of two events leaves the combined limit shown in Fig. o nearly unchanged below \(q_{10}\) GeV and allows for a modest strengthening in the limit above this mass.

Z. Ahmed et al., CDMS Collaboration, arXiv:0912.3592
Experimental Challenges

Signal is elastic $\chi N \rightarrow \chi N$ with small recoil energy $E_N \sim 10$ keV

- Not much of an experimental signature to reject background

Background sources include

- $N \rightarrow N' + \alpha$ or $e^-$
- $\gamma e \rightarrow \gamma e$
- $nN \rightarrow nN$
- $\nu N \rightarrow \nu N$

To combat the backgrounds

- Screen everything for radiopurity
- Use multiple signatures
- Go deep underground

Cross sections are small

- Need large detector mass
- But what?
Liquid Xenon

WIMP-nucleus cross section $\propto A^2$
- de Broglie wavelength $\sim$ nuclear radius
Xe ($A = 131.3$) gives high signal rate
- 100 kg-year exposure can probe $10^{-45}$ cm$^2$

Key liquid Xe properties
- High density: 3 g/cm$^3$
- High boiling point: 165K
- Good scintillator: 42 photons/keV at 175 nm
- High ionization yield: $W = 15.6$ eV
- As a liquid, it can be circulated and purified
- No long-lived radioactive isotopes
  - $^{85}$Kr must be removed by charcoal chromatography

Cost: $1000$/kg
Two-Phase Xe Detector

PMTs collect prompt (S1) and proportional (S2) light
- S1-S2 delay → Drift length
- S2 light pattern → Horizontal location

S2/S1 ratio differs markedly between electron and nuclear recoils
- Nuclear recoils have higher ionization density → higher recombination probability → higher S1 yield
- >98.5% rejection of EM backgrounds
**S2/S1 Ratio**

- **XENON10 calibration data** show clean discrimination between electron and nuclear recoils
- log(S2/S1) normalized to the electron recoil data is used to select the signal candidates
**Scaling Up**

Liquid Xe experiments scale well

- Readout $\propto (\text{volume})^{2/3}$
- Good self shielding: $X_0 = 2.77$ cm

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<th>XENON10</th>
<th>LUX</th>
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<tr>
<td>Total Xe</td>
<td>22 kg</td>
<td>350 kg</td>
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<tr>
<td>Fiducial</td>
<td>5.4 kg</td>
<td>100 kg</td>
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<td>Live time</td>
<td>58.6 days</td>
<td>100 days</td>
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<th>Homestake</th>
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technology to achieve <1 bkgd.

- Xe purification system has a $\times 100$ capacity (300 kg/day)
- Ultra-low activity Ti vacuum vessel replaces SS + Cu
- PMTs have lower activity (9/3 mBq of U/Th per tube) and higher QE (27%)
- 183 m$^3$ purified water tank shields the detector from neutrons
Xenon Purification System

Purification of liquid xenon is crucial:
- Light-absorbing impurities → scintillation light is lost
- Electronegative impurities → electrons are lost during the drift

Gas-phase recirculation system through heated getter
- Evaporate liquid Xe → purify Xe gas → re-condense
- Used successfully in XENON10 and ZEPLIN II

Size of LUX demands larger flow rate → higher cooling power
- 300 kg recirculation per day = 200W = 100 litre of liquid N₂ per day

Heat-exchanger system reduces the cooling power by 96%
- Demonstrated 400 kg/day throughput at 18W
- cf. XENON10 system did 40 kg/day at ~30W

$^{85}$Kr is removed by chromatography through a charcoal column
- Bolozdynya et al., NIM A579, 50-53 (2007)
Energy Threshold

Energy threshold is determined by the S1 light yield
- Different for electron vs. nuclear recoil

**XENON10 performance:**
- S1 light yield = 1 phe/keVnr
- Analysis cut = 4.5 keVnr
- PMT was R8520 (1” sq., QE = 14%)

**LUX differs only slightly**
- PMT is R8778 (2” dia., QE = 27%)
  - Less coverage, better QE
- Bottom grid is more transparent
- Expect 1 phe/keVnr

We assume 5 keVnr for estimating our physics reach
Radioactivity Control

\(\gamma\)-ray background must be moderately low
- Suppressed by self shielding and S1/S2 ratio

PMTs have been screened for radioactivity
- <9/3 mBq of U/Th per tube

Vacuum vessel uses high-purity titanium
- XENON10 used SS combined with Cu shielding
- Ti has low U/Th/K content and mechanically strong
- Top flanges are made of SS
- Cu shielding between the flange and the top PMTs

All internal components are screened, and kept in clean rooms to avoid Rn exposure
Water Shield

Detector is suspended inside a 183 m$^3$ purified water tank

- Fast neutrons generated in the rocks by cosmic rays are efficiently absorbed

PMTs inside the water tank will veto cosmic rays passing through the water

- Minor component of the electron-recoil background
LUX Collaboration

Brown, Case Western, LBNL, Harvard, LLNL, Maryland, Texas A&M, UC Davis, Rochester, South Dakota, Yale

- Funded by DOE & NSF
LUX Detector

1. Water Shield
2. Thermosyphon
3. Xenon recirculation and heat exchanger
4. Time Projection Chamber
5. Photomultiplier Tubes
6. Inner Titanium cryostat
7. Superinsulation
8. Titanium cryostat

- **350 kg liquid xenon**
- Photomultiplier Tubes (PMTs) detect scintillation and ionization light of events inside the detector. They are sensitive to xenon 175 nm (UV) light and are able to detect single photons. There are 122 PMTs in the detector.
- In addition to liquid xenon's self-shielding, the 8-meter diameter by 6-meter height reduces gamma background by 10 orders of magnitude.
- Xenon is constantly being recirculated in and out of the detector for purification. The heat exchanger transfers the heat load from the incoming xenon gas to the outgoing xenon liquid.
- The PMT hit pattern provides x-y localization of an event, while the time between primary (S1) and secondary (S2) scintillation signals provides z-localization.
- The CHF, 200811LUXAnatomy diagram illustrates the anatomy of the LUX Detector.
Detector Internals

- HV Grids in place and tested

- 122 2" PMT R8778
  - 175 nm, QE > ~30%
  - U/Th ~9/3 mBq/PMT
  - All tested in LUX 0.1 program

Assembly taking place at Texas A&M since early 2009

- Dodecagonal field cage + PTFE reflector panels

- Copper PMT holding plate
Internal Assembly

Assembly in progress at Texas A&M since early 2009
LUX0.1

Prototype LUX operating on surface at Case Western Reserve University
Includes all LUX components:
- Cryogenics
- Recirculation and purification
- Slow control and safety systems
- PMTs and HV
- Readout electronics
- Data acquisition
- Analysis software

60 kg of liquid Xe viewed by 4 PMTs
- Active region is ~5 cm tall
Xenon Purification System

Operating on LUX0.1 containing 60 kg Xe

- 9 hour purification time constant
- Electron drift length >2m in 80 hours

NB: internal surface area of LUX0.1 is identical to the full-scale LUX
Sanford Laboratory

Feasibility demonstration prior to DUSEL

- $70M of $100M comes from a private donor
- 4,850 ft level (Davis Lab) outfitted for science programs
- LUX and Majorana are the initial occupants

Cavern will be ready in May 2010

- Two-storey 55’x30’x32’ space for LUX detector + clean room, control room, counting facility
Davis Lab 1964/2009
Surface Facility

Full scale LUX assembled and deployed in a surface building

- Building ready for occupancy as of November 30
- Exact duplicate of the underground layout except for the smaller (3 m) water tank

Detector integration in Jan-Feb followed by surface operation with 350 kg liquid Xe

- Detector will be moved as-is when the 4850L lab is ready
LUX Sensitivity

Will reach $\sigma_{\chi p} = 5 \times 10^{-46} \text{ cm}^2$
in 100 live days

- 50-to-100-fold improvement over the existing limit

If $\sigma_{\chi p} = 5 \times 10^{-45} \text{ cm}^2$ and $m_\chi = 100 \text{ GeV}$, we will see:

Electron recoil bkgd, 100 days

100 GeV WIMP signal

Cross-section [cm$^2$] (normalised to nucleon) vs. WIMP Mass [GeV/c$^2$]

XENON10 (2007)
ZEPLIN III (2008)
CDMS II (2009)

http://dmtools.brown.edu/
Gaitskell, Mandic, Filippini
Scaling Up Beyond LUX

How far can we scale the liquid Xe detector technology?

- Size isn’t an issue — 3 tonne of liquid Xe is just 1 m$^3$
- Self-shielding improves with size — $\gamma$-ray background less important

Xe procurement: $1M$/tonne

- World production is 45 tonne/year

Must keep the backgrounds low

- Instrumental radioactivity limits the fiducial volume
  - Develop 3” PMTs with <1/1 mBq U/Th per tube
  - Control Rn contamination during the assembly
- Radioactivity inside Xe dominated by $^{85}$Kr ➔ Bump up the purification system
- Cosmogonic neutrons ➔ Active shielding

Ultimate limit: neutrino-nucleus coherent scattering @ 20 tonne

- Due to $^{8}$B solar, atmospheric, and supernova neutrinos
- Fundamental limit of direct WIMP searches
LZS/LZD Projects

LZS (Sanford) = LUX scaled up to 1500 kg (1200 kg fiducial)
- Joint collaboration of LUX and ZEPLIN-III
- LUX infrastructure designed to accommodate LZ
- Liquid scintillator veto surrounds the detector to reduce cosmogenic neutron background and forward Compton scattering background
- Proposed for construction in 2010–2011 followed by 2012–2013 operation
- $\sigma_{\chi N} = 2 \times 10^{-47} \text{ cm}^2$ in 2 years

LZD (DUSEL) = 20 tonne concept
- 2 m diameter x 2 m height
- $\sigma_{\chi N} = 2 \times 10^{-49} \text{ cm}^2$ in 3 years
LZS/LZD Sensitivity

LUX: 100 kg x 300 days (2010–2011)

LZS: 1,200 kg x 500 days (2012–2013)

LZD: 13,500 kg x 1000 days (2016–2019)
Summary and Prospect

Dark Matter is a cosmology problem seeking a particle physics solution

- Evidences point to WIMPs waiting to be discovered
- Theoretical models suggest $\sigma_{\chi N} \approx 10^{-44} - 10^{-45} \text{ cm}^2$

LUX experiment will use proven liquid Xe technology to reach $\sigma_{\chi N} = 5 \times 10^{-46} \text{ cm}^2$

- Covers 2-orders of magnitude of the theoretically favored region
- Dark Matter search run will start in 2010

LZS/LZD will push the sensitivity to $< 10^{-48} \text{ cm}^2$ by 2019

We may know what Dark Matter is within this decade