Measurement of Ultra-low Energy Nuclear Recoils in the LUX Detector Using a D-D Neutron Generator

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Postdoc position available

• Postdoc position available in Brown Particle Astrophysics Group

• If interested, please contact group leader Richard Gaitskell

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Conservative Nuclear Recoil Light and Charge Yields Assumed for LUX 2014 PRL

- Modeled Using Noble Element Simulation Technique (NEST)
  - Szydagis et al., arxiv:1106.1613
- NEST based on canon of existing experimental data.
- Artificial cutoff in light and charge yields assumed below 3 keVnr, to be conservative.
- Includes predicted electric field quenching of light signal, to 77-82% of the zero field light yield

Artificial 3 keVnr Ionization Cut-off (same as with scintillation)
By the way, LUX has in situ calibration from 190 eV x-ray

- Using x-rays from $^{127}$Xe electron capture
- Events unambiguously tagged by coincident 203 keV gamma
- Provides in situ measurement of ER ionization yield to energies as low as 190 eV

From recent $^{127}$Xe work by Dongqing Huang (Brown University): http://pa.brown.edu/talks_files/2015_dqhuang_TAUP.pdf
Neutron Conduit Installed in the LUX Water Tank
Adelphi Technology, Inc. DD108 Neutron Generator Installed Outside LUX Water Tank

- Neutron generator/beam pipe assembly aligned 17 cm below liquid level in LUX active region to maximize usable single / double scatters
- Beam leveled to ~1 degree
- 107 live hours of neutron tube data used for analysis
\[ E_r = E_n \frac{4m_n m_{xe}}{(m_n + m_{xe})^2} \frac{1 - \cos \theta}{2} \]
Monochromatic 2.5 MeV neutrons

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top hit pattern: x-y localization

Δt : z' separation

θ : energy calculation

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Monochromatic 2.5 MeV neutrons

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\[ \Delta t : z' \text{ separation} \]

\[ \theta : \text{energy calculation} \]

Samuel Chan, Carlos Faham for the LUX Collaboration
Beam Projection in Active Region

- The shine from neutron scatters in passive detector materials is visible.

- Historically, NR calibrations have significant systematics associated with neutrons scattering in passive material.

- We can fiducialize away from such backgrounds!

```
0  50  100  150  200  250  300

\textbf{x'} \text{perpendicular to neutron tube [cm]}
```

```
0  50  100  150  200  250  300

\textbf{y'} \text{Distance into LXe [cm]}
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Neutron Beam Energy Purity

- After application of 15 cm depth-into-LXe beam purity cut
- This cut eliminates shine from passive materials and ensures 95% of neutrons in beam sample have energy within 4% of 2.45 MeV.
- Cut based on simulation, but we are showing REAL DATA
Observed Ionization Signal

- Event Selection Cuts
  - Event Identification
    - Select double scatters
    - Determine vertex ordering via scattering geometry only
  - Neutron Beam Energy Purity
    - Enforced via position of scatters along beam line / depth into active LXe
    - After geometry cut, 95% of neutrons have energy within 4% of 2.45 MeV
  - Data Quality
    - Ensure quiet detector conditions
    - Ensure properly reconstructed events
  - Cuts are flat for $S_2[1, y']$ (first scatter along beam direction) in energy region of interest

Grey Points - Individual double scatter events

Double Scatter ($S_1$, $2xS_2$s > 50 phe)
What does a 1 keV\textsubscript{nra} double scatter look like?

- x, y, z position of both S2 vertices from 1 keV\textsubscript{nra} double scatter in REAL DATA

\textbf{2.45 MeV neutron beam}
What does a 1 keV \(\text{nra}\) double scatter look like?

**S1 and 2x S2 summed across all channels**

- Energy deposited at first vertex: \(1.0 \pm 0.5 \text{ keV}_{\text{nra}}\)
- Scattering angle: \(13 \pm 4\) degrees
Ionization Signal Absolutely Measured below 1 \( \text{keV}_{\text{nra}} \) in LUX

- Reconstruct number of electrons at interaction site by matching ionization signal model with observed event distribution using extended maximum-likelihood

- Red systematic error bar shows common scaling factor uncertainty. Dominated by uncertainty in electron extraction efficiency

- Lowest event energy included for analysis is 0.3 \( \text{keV}_{\text{nra}} \)

Grey Points - Individual double scatter events
Magenta Crosses - Error bars for individual event from best 10% from each bin
Blue Crosses - Reconstructed number of electrons at interaction site accounting for threshold, resolution, and Eddington bias effects in signal analysis
Black Dashed Line - Szydagis et al. (NEST v1.0) Predicted Ionization Signal at 180 V/cm
Ionization Signal Absolutely Measured below 1 keV\textsubscript{\text{nra}} in LUX

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LUX 2014 PRL Conservative Threshold Cut-Off

Reconstructed Number of Electrons with Associated Statistical Uncertainty
Example Error Bars for Individual Events
Sys. uncertainty due to pos. rec. energy bias correction
Ionization Yield Absolutely Measured below 1 keV\textsubscript{nra} in LUX

- Red error bars show systematic uncertainties
  - (1σ) bar dominated by uncertainty in electron extraction efficiency
  - (flat) bar accounts for detector parameter uncertainties
  - Pos. Rec. bias correction error bars compensate for modest Eddington bias due to pos. rec. uncertainties
- Updated analyses in upcoming LUX Run03 papers have revised g1 and g2 values using data driven S1 vs. S2 anti-correlation
  - Provides strong determination of absolute normalization of yields
- Shifts measured Qy lower by ~10%

Blue Crosses - LUX Measured Qy; 180 V/cm (absolute energy scale)
Green Crosses - Manzur 2010; 1 kV/cm (absolute energy scale)
Orange Crosses - Manzur 2010; 4 kV/cm (absolute energy scale)
Purple Band - Z3 Horn Combined FSR/SSR; 3.6 kV/cm (energy scale from best fit MC)
Teal Lines - Sorensen IDM 2010; 0.73 kV/cm (energy scale from best fit MC)
Black Dashed Line - Szydagis et al. (NEST v1.0)
Predicted Ionization Yield at 180 V/cm

LUX 2014 PRL Conservative Threshold Cut-Off

Double Scatter (S1, 2xS2s > 33 phe)

Inferred Ionization Yield [electrons / keV\textsubscript{nra}]

Energy Measured from Scattering Angle [keV\textsubscript{nra}]

Reconstructed Ionization Yield with Associated Statistical Uncertainty

Sys. uncertainty due to pos. rec. energy bias correction
Sys. uncertainty (flat)
Sys. uncertainty (±1σ)

Blue Crosses - LUX Measured Qy; 180 V/cm (absolute energy scale)
Green Crosses - Manzur 2010; 1 kV/cm (absolute energy scale)
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Predicted Ionization Yield at 180 V/cm
Example: $S_{1c}$ Spectrum from 400-500 $S_{2_{sc}}$

- Use absolutely calibrated $S_2$ yield to set energy scale for extraction of $L_y$ from D-D neutron single scatter event population
- Measure number of $S_1$ photons produced at interaction site for fixed slice in $S_{2_{sc}}$ (absolutely calibrated by LUX D-D $Q_y$)
- For each fixed $S_{2_{sc}}$ bin, determine $L_y$ via unbinned maximum likelihood optimization comparing simulated reconstructed $S_1$ spectra to data
  - Both absolute number of events and spectrum shape incorporated into optimization
**L$_{\text{eff}}$ Measured in LUX Using Absolute Energy Scale**

- LUX L$_y$ values reported at 180 V/cm
- X error bars representative of error on mean of population in bin
- Energy scale defined using LUX measured Q$_y$
- Method can be extended below existing 1.2 keV$_{nrS2}$ point
- $^{32}$m Kr light yield at 32.1 keV measured to be 45.7 ± 3.13 photons/keV using same D-D beam fiducial

**Blue Crosses - LUX Measured L$_{y}$; reported at 180 V/cm (absolute energy scale)**

**Green Crosses - Manzur 2010; 0 V/cm (absolute energy scale)**

**Purple Band - Horn Combined Zeplin III FSR/SSR; 3.6 kV/cm, rescaled to 0 V/cm (energy scale from best fit MC)**

**Orange Crosses - Plante 2011; 0 V/cm (absolute energy scale)**

**Grey Crosses - Aprile 2009 (absolute energy scale)**

**Black Dashed Line - Szydagis et al. (NEST v1.0) Predicted Scintillation Yield at 181 V/cm**
Summary of LUX D-D results

- LUX absolute nuclear recoil calibration performed using mono-energetic D-D neutrons in-situ

- Clear confirmation of the response used in the first LUX WIMP search analysis with an order of magnitude improvement in calibration uncertainties

- The 2014 PRL WIMP analysis only assumed a detector response at and above 3 keVnr

- D-D neutron calibration technique allows us to calibrate detector response in region well below this, and provides a significant improvement in LUX sensitivity to low mass WIMPs using existing 2014 PRL WIMP search dataset

- Coming soon

  - LUX paper on D-D results
  - NEST fit to D-D light and charge yields
  - Updated WIMP search limit from reanalysis of 2014 PRL dataset

- But that isn’t all…
Planned enhancements to the D-D calibration technique for TPCs

We’re pursuing several strategies to extend the in situ D-D NR calibration even lower in energy with smaller uncertainties for the general calibration of TPCs.

1. Reduction of D-D neutron bunch width time structure
2. Creation of a mono-energetic 272 keV neutron source
3. Direct, absolute measurement of $L_\gamma$ using neutron scattering kinematics
Reduction of D-D neutron bunch width time structure

- DD beam-on time functions as a proxy for the $t_0$ even in the absence of an S1
  - Removes dependence upon S1 production/detection for S2 only double scatter $Q_y$ measurement
- For reference, without an S1 we can fiducialize in Z (given 1.5 mm/us) with a precision:
  - 100 us (current generator spec) neutron pulse => 15 cm Z fiducialization precision
  - 10 us neutron pulse => 1.5 cm Z fiducialization precision
    - Z fiducialization precision equal to that from x, y reconstruction (and < diameter of neutron tube)
  - 1 us neutron pulse => 0.15 cm Z fiducialization precision
    - Z fiducialization precision equal to standard (1 S1, 1 S2) technique (and << diameter of neutron tube)
Reduction of D-D neutron bunch width time structure: S1 photon statistics

- Can identify small S2 events from D-D scatters and look at the statistics of the associated S1 signal. For given S2 size, can measure 0, 1, 2, ... photon events.

- In addition to advanced no-S1 studies, narrow trigger pulse allows for powerful reduction and understanding of calibration backgrounds.
Can identify small S2 events from D-D scatters and look at the statistics of the associated S1 signal. For given S2 size, can measure $0$, $1$, $2$, … photon events.

In addition to advanced no-S1 studies, narrow trigger pulse allows for powerful reduction and understanding of calibration backgrounds.
Creation of a collimated, mono-energetic 272 keV neutron source

- D-D generator source out of line with the neutron conduit to suppress direct 2.45 MeV neutrons

- 700 bar D₂ gas cylinder in-line with the neutron conduit to function as a D-D neutron reflector

- Small solid angle presented by 5 cm diameter neutron conduit ensures only neutrons that backscatter at near 180° (272 keV) are incident upon the large LXe TPC
Creation of a collimated, mono-energetic 272 keV neutron source

- Neutron beam energy purity
  - For 700 bar D$_2$ target, 94% of reflected neutrons are within +/-10% of central peak value of 272 keV

- Observed event rate
  - Useful reflected flux incident on the detector is 1/375x the flux of a direct line of sight D-D source with same intensity
  - Expect to achieve useful event rates enhanced above (7.5x) standard line-of-sight 2.45 MeV D-D calibrations in the range 1-4 keV$_{nr}$
    - Increase in neutron generator flux, differential spectrum enhancement, and no inelastic losses for 272 keV neutrons

- The same 13° scatter waveform shown earlier, identified in existing D-D data, would be a 110 eV nuclear recoil using 272 keV incident neutrons
  - Can study Q$_y$ in lowest ever regime where expectation for signal is ~1-2 ionization electrons!

Simulations work by Casey Rhyne (Brown University)

Deuterium angular scattering cross section in LAB frame

700 bar D$_2$ Gas in cylinder
(Ø5cm x 20cm)
- n mfp = 17 cm @ 2.45 MeV
- Density = 0.08 g D/cm$^3$

Preliminary
Direct, absolute measurement of $L_y$ using neutron scattering kinematics

- But 272 keV neutrons are also 3x slower than direct 2.45 MeV D-D neutrons...
- Double scatter events with 30 cm vertex separation => 42 ns ToF for 272 keV neutrons between vertices
  - We expect an experiment could observe 100s of such events given reasonable calibration runtimes (weeks) in a large LXe TPC
  - If able to achieve even longer path lengths (>50 cm), then >70 ns separation between vertices is possible
- Can distinguish photons in $S_{1A}$ from those in $S_{1B}$
- As in current $Q_y$ measurement, can use angle to absolutely reconstruct the deposited energy for vertex A
  - Can now use direct angle based energy measurement for $L_y$ determination using $S_{1A}$ photon count
Postdoc position available

- Postdoc position available in Brown Particle Astrophysics Group
- If interested, please contact group leader Richard Gaitskell
  - Richard_Gaitskell@brown.edu
Consider $\text{D}_2\text{O}$ for D-D neutron backscatter target

- Alternate D-loaded backscatter target: heavy water
- For heavy water, 56% of reflected neutrons are within +/-10% of central peak value of 272 keV

Simulation

Simulations work by Casey Rhyne (Brown University)
The LUX Dark Matter Detector

- What is LUX?
  - a particle detector
  - a monolithic wallless fiducial region within 370 kg, two-phase XeTPC
  - viewed by 122 Photomultiplier Tubes
  - able to reconstruct (x,y,z) for each event
  - exceptional self-shielding from outer xenon layer
  - discrimination between electronic and nuclear recoils (99.6%)

- How would LUX see dark matter?
  - it detects scintillation photons and ionized electrons created by particle interactions
  - if dark matter interacted with a xenon atom, energy transferred to that atom would be visible to LUX
  - $g_1 \sim O(0.10)$ and $g_2 \sim O(10)$ are the amplification factors for each quanta
  - $n_\gamma$ and $n_e$ are the fundamental measured quantities
LUX has extremely low background

- 4850 ft (1492 m) underground in the black hills of South Dakota (4300 meters water equiv.) ... reduces muon flux to <1 muon per day

- surrounded by a 7.6 m diameter water shield ... reduces gamma and neutron backgrounds to <1 projected event in 300 days of searching

- limiting factor is detector construction materials ... this limit is <2 background events per DAY in the central 118 kg target in the energy window of interest... and is decreasing
Measuring the Scintillation Yield

- Use single scatters with suitable selection criteria
- MC using measured LUX D-D charge yield to simulate expected single scatter energy spectrum with LUX threshold, purity, electron extraction, energy resolution effects applied
- Simulation uses JENDL-4.0 angular scattering cross-sections with isotope selection determined based upon natural abundance and total elastic cross-sections
- $L_y$ measurement range is 0-900 phe $S^{sc}_{2}$ using bins of 100 phe
- Simulation event distribution is normalized outside of $L_y$ measurement range using $900 < S^{sc}_{2} < 1500$ phe

![Graph showing single scatter data with counts on the y-axis and S2sc (phe) on the x-axis.]

Single Scatter (S1, 1xS2s > 50 phe)
Measuring the Scintillation Yield

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- \( L_\gamma \) measurement range is 0-900 phe \( S_{2_{sc}} \) using bins of 100 phe

- Simulation event distribution is normalized outside of \( L_\gamma \) measurement range using \( 900 < S_{2_{sc}} < 1500 \) phe

Select slice of \( S_{2_{bc}} \) to use for \( S_1 \) comparison
Measuring the Scintillation Yield

- Use single scatters with suitable selection criteria
- MC using measured LUX D-D charge yield to simulate expected single scatter energy spectrum with LUX threshold, purity, electron extraction, energy resolution effects applied
- Simulation uses JENDL-4.0 angular scattering cross-sections with isotope selection determined based upon natural abundance and total elastic cross-sections
- \( \text{L}_\text{y} \) measurement range is 0-900 phe \( S_2\text{sc} \) using bins of 100 phe
- Simulation event distribution is normalized outside of \( \text{L}_\text{y} \) measurement range using \( 900 < S_2\text{sc} < 1500 \) phe

Single Scatter (S1, 1xS2s > 50 phe)

Select slice of \( S_2\text{bc} \) to use for S1 comparison

Normalize simulation spectrum using this region
Electron Recoil Qy Comparison with Tritium and NEST

$^{127}\text{Xe}$ work by Dongqing Huang (Brown University): http://pa.brown.edu/talks_files/2015_dqhuang_TAUP.pdf


Low Mass WIMPs - Fully Excluded by LUX

- LUX (2013)-85 live days
- LUX +/-1σ expected sensitivity
- CDMS II Si Favored
- CoGeNT Favored
- DAMA/LIBRA Favored
- CRESST Favored
- >20x more sensitivity
- XENON100(2012)-225 live days
Spin-Independent Sensitivity

LUX (+/-1σ expected sensitivity)

ZEPLIN III

CDMS II Ge

Edelweiss II

XENON100(2011)-100 live days

XENON100(2012)-225 live days

LUX (2013)-85 live days

WIMP–nucleon cross section (cm$^2$) vs. $m_{\text{WIMP}}$ (GeV$^2$/c$^2$)
Projected LUX 300 day WIMP Search Run

- LUX 300 day run is underway
- Extending sensitivity by another factor 5
- Even though LUX sees no WIMP-like events in the current run, it is still quite possible to discover a signal when extending the reach
- LUX does not exclude LUX

- WIMPs remain our favored quarry
- LZ 20x increase in target mass