TWO-PHASE DETECTORS USING THE NOBLE LIQUID XENON

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Oxford University – 18th October 2016
OUTLINE

• Two-phase xenon for (dark) radiation detection
  • Instrumenting a liquid xenon target

• Liquid xenon response(s) to radiation
  • Physics underlying the detector response
THE LUX EXPERIMENT

250 kg active mass
~100 kg fiducial

Relevant recent papers:
arXiv:1512.03133
arXiv:1608.05381
arXiv:1610.02076
arXiv:1608.07648
LUX-ZEPLIN (LZ)

7,000 kg active mass
≈5,600 kg fiducial

- Instrumentation conduits
- Water tank
- Gadolinium-loaded liquid scintillator veto
- Liquid xenon heat exchanger
- High voltage feedthrough
- 120 veto PMTs
- 7 tonne liquid xenon time-projection chamber
- 488 photomultiplier tubes (PMTs)
  Additional 180 xenon “skin” PMTs

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TWO-PHASE XE DETECTOR / LXe-TPC

~1 keV e⁻

Vadim Lebedenko
1939 – 2008
TWO-PHASE XE DETECTOR / LXe-TPC

- **S1: Prompt scintillation**
  - Light yield: >60 ph/keV (0 field)
  - Scintillation light: 178 nm (VUV)
  - Nuclear recoil threshold ~3-6 keV

- **S2: Ionisation via electroluminescence**
  - Sensitive to single ionisation electrons
  - S1+S2 > vertex reconstruction, discrimination
  - Nuclear recoil threshold <1 keV

- **WIMP target**
  - Dense medium (3 g/cm³), high Z (54), high A (131)
  - Spin independent WIMP-nucleon scattering rate dR/dE~A²
  - Odd-neutron isotopes (¹²⁹Xe, ¹³¹Xe) enable spin-dependent sensitivity
  - No intrinsic backgrounds (¹²⁷Xe, ¹²⁹m/¹³¹mXe, ¹³⁶Xe subdominant)
  - Others dispersible backgrounds can be controlled (⁸⁵Kr, ²²²/²²⁰Rn)
WIMP-NUCLEUS ELASTIC SCATTERING

The ‘spherical cow’ galactic model
- DM halo is 3-dimensional, stationary, with no lumps
- Isothermal sphere with density profile $\rho \propto r^{-2}$
- Local density $\rho_0 \sim 0.3 \text{ GeV/cm}^3$ ($\sim 1/\text{pint}$ for 100 GeV WIMPs)

Maxwellian (truncated) velocity distribution, $f(v)$
- Characteristic velocity $v_0=220 \text{ km/s}$
- Escape velocity $v_{\text{esc}}=544 \text{ km/s}$
- Earth velocity $v_E=230 \text{ km/s}$

Nuclear recoil energy spectrum [events/kg/day/keV]

$$\frac{dR}{dE_R} = \frac{\rho_0 \sigma_A}{2m_\chi \mu_A^2} F^2(q) \int_{v_{\text{min}}}^{v_{\text{max}}} \frac{f(\vec{v})}{v} d^3v$$

$$\frac{dR}{dE_R} \approx \frac{R_0}{E_0 r} e^{-E_R/E_0 r}, \quad r = \frac{4m_W m_T}{(m_W + m_T)^2} \leq 1$$

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XENON AS A WIMP TARGET

Xenon Isotopes

- 9 ‘stable’
- 2νββ decays
- Short-lived

High atomic mass (SI XS)
Odd-neutron isotopes (SD XS)

<table>
<thead>
<tr>
<th>AZ</th>
<th>T$_{1/2}$ or %</th>
<th>J$^p$</th>
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<tbody>
<tr>
<td>$^{122}\text{Xe}$</td>
<td>20 h</td>
<td>0$^+$</td>
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<tr>
<td>$^{123}\text{Xe}$</td>
<td>2.1 h</td>
<td>(1/2)$^+$</td>
</tr>
<tr>
<td>$^{124}\text{Xe}$</td>
<td>0.10%</td>
<td>0$^+$</td>
</tr>
<tr>
<td>$^{125}\text{Xe}$</td>
<td>17 h</td>
<td>(1/2)$^+$</td>
</tr>
<tr>
<td>$^{126}\text{Xe}$</td>
<td>0.09%</td>
<td>0$^+$</td>
</tr>
<tr>
<td>$^{127}\text{Xe}$</td>
<td>36 d</td>
<td>(1/2)$^+$</td>
</tr>
<tr>
<td>$^{128}\text{Xe}$</td>
<td>1.91%</td>
<td>0$^+$</td>
</tr>
<tr>
<td>$^{129}\text{Xe}$</td>
<td>26.4%</td>
<td>(1/2)$^+$</td>
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<tr>
<td>$^{130}\text{Xe}$</td>
<td>4.1%</td>
<td>0$^+$</td>
</tr>
<tr>
<td>$^{131}\text{Xe}$</td>
<td>21.2%</td>
<td>(3/2)$^+$</td>
</tr>
<tr>
<td>$^{132}\text{Xe}$</td>
<td>26.9%</td>
<td>0$^+$</td>
</tr>
<tr>
<td>$^{133}\text{Xe}$</td>
<td>5.2 d</td>
<td>(3/2)$^+$</td>
</tr>
<tr>
<td>$^{134}\text{Xe}$</td>
<td>10.4%</td>
<td>0$^+$</td>
</tr>
<tr>
<td>$^{135}\text{Xe}$</td>
<td>9.1 h</td>
<td>(3/2)$^+$</td>
</tr>
<tr>
<td>$^{136}\text{Xe}$</td>
<td>8.9% (2.2×10$^{21}$ y)</td>
<td>0$^+$</td>
</tr>
</tbody>
</table>
WIMP signal: elastic scattering producing nuclear recoils (NR) in the keV range: primary recoil produces small atomic cascade
  • Also neutrons, neutrinos (ν-A)

Background particles interact mostly with atomic electrons producing (keV) electron recoils (ER)
  • Gammas, betas, neutrinos (ν-e)
  • Also some signal models

Our goal:
To detect efficiently and discriminate between low-energy NR and ER, in as large a detector as possible
THE EXPERIMENTAL CHALLENGE

• Low-energy particle detection is easy ;)  
  E.g. Microcalorimetry with Superconducting TES  
  Detection of keV particles or photons with eV FWHM

• Rare event searches are also easy ;)  
  E.g. Super-Kamiokande contains 50 kT water  
  Cut to ~20 kT fiducial mass: huge self-shielding effect

• But doing both is hard!  
  Small is better for collecting signal  
  Large is better to shield backgrounds

• And there is no trigger...

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KEY DETECTOR REQUIREMENTS

The success of the two-phase xenon technology relies on three aspects:

- **Low energy threshold (mostly S1)**
  - Detectable WIMP scattering rate
  - Scintillation yield, VUV reflectivities, VUV QE, PMTs in the liquid phase

- **Accurate 3D imaging (mostly S2)**
  - Background reduction (self-shielding)
  - Electroluminescence yield, electric fields, electron lifetime, PMTs in the gas phase

- **ER/NR discrimination (S1 + S2)**
  - Background reduction (NR selection)
  - High yields, uniform detector, no ‘funny’ event topologies
LXE SELF-SHIELDING

- Self-shielding of external backgrounds
- Interesting challenge for calibration...

![Graphs showing neutron and gamma interactions in LXe](image)

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LXE RESPONSE TO RADIATION

- Understanding the detector response to nuclear recoils (NR) and electron recoils (ER) down to detection threshold is crucial.
- S1 & S2 depend on: particle species, recoil energy, electric field.
- Electron-ion recombination is a key parameter.
- Model with single $W$-value for total quanta works!

$$E = (n_e + n_\gamma) \cdot W.$$ $$E_{nr} = \mathcal{L}^{-1} \cdot (n_e + n_\gamma) \cdot W.$$
WHAT IS REQUIRED FOR A JOB WELL DONE

• Understand the detector
  • S1 (photon) detection, inc. measurement of S1 quantum
  • S2 (electron) detection, inc. measurement of S2 quantum
  • S1 & S2 photon detection efficiencies (inc. flat-fielding)
  • S1 & S2 absolute gains (g1, g2)
    • Relate detected quanta to energy deposit using known W-value

• Understand LXe physics in ROI
  • ER scintillation & ionisation yields
    • and fluctuations
  • NR scintillation & ionisation yields
    • and fluctuations
DETECTING PHOTONS (mostly S1)

Quartz-windowed PMTs work very well at 178 nm
Resolved PMT backgrounds over last decade
Must calibrate QE in VUV: sometimes 2 phe/photon...

• Photon counting in PMT waveforms: #phe > #phd
• Improved resolution & linearity!

arXiv:1506.08748
DETECTING PHOTONS (mostly S1)

PTFE is a magical material

• Very high VUV reflectance when immersed in LXe; very low background; low outgas, compatible with LXe; great electrical properties,... We got lucky!

• External measurement of LUX PTFE
  • Best fit R=97.8% (>97.5% @95% CL) (F. Neves IDM2016)
DETECTING ELECTRONS (S2)

- Drifting electrons from vertex to surface: need high e-lifetime
- Cross-phase electron emission requires at high fields (>5 kV/cm)
- Electroluminescence in the vapour phase provides high gain for ionisation channel – and transduces signal to VUV photons

![Graph showing emission probability and electroluminescence yield](image)
DETECTING ELECTRONS (S2)

- Single electron response: absolute calibration of S2 channel
- Electroluminescence gain depends on several parameters which can vary during a long run (pressure, fields, liquid level,...)
- SE signal can be tracked to % level during run
- Pure sources of SE signals, e.g. VUV photoionisation of impurities
S1 & S2 PDEs – FLATFIELDING WITH $^{83m}\text{Kr}$

- X,Y,Z response calibration with dispersed $^{83m}\text{Kr}$ radioisotope
  - Routine injection, decays within detector, emitting 2 CE (T$_{1/2}$ = 1.86 hrs)

Kr-83m calibration source:
Rb-83 infused into zeolite, located within xenon gas plumbing
S1 & S2 PDEs – FLATFIELDING WITH $^{83m}$Kr

Flat-fielding light collection – and field
- g1 and g2 corrected to detector centre
- Field is non-uniform due to leakage through grids and other factors
- Varying field $\rightarrow$ light yield, drift speed,...
S1 & S2 ABSOLUTE GAINS: ER ‘DOKE PLOT’

- Mono-energetic ER sources in the mean-yields plane (5-662 keV)
- Line fit and W-value = 13.7 eV give absolute number of quanta:
  \[ \langle S1c[phd] \rangle = 0.117 \pm 0.003 \cdot n_{ph}, \langle S2c[phd] \rangle = 12.1 \pm 0.8 \cdot n_e \]

\[ E_{total} = W \cdot (n_\gamma + n_e) \]
ER TRITIUM CALIBRATION (0–18 keV)

arXiv:1512.03133

• Injection of CH$_3$T through gas system, removal through getter
• Extensive R&D at UMD followed by tests in LUX using CH4
• Progressive injections of CH$_3$T to confirm no residual background

![Graph showing data related to ER tritium calibration](image-url)
ER TRITIUM CALIBRATION (0–18 keV)

• Main CH$_3$T calibration campaign: 180,000 events
• Reconstruct spectrum using Doke Plot result
• Constrain detection threshold, mean ER yields, and ER recombination fluctuations
• Absolute ER light and charge yields for LXe (+ recombination)
• Essential to advance modelling – NEST tool (Szydagis et al)
• NEST is in turn needed to really understand WIMP sensitivity
ER TRITIUM CALIBRATION (0–18 keV)

- Recombination fraction and its fluctuations for electron recoils (S1 and S2 event by event)
RECOMBINATION

1610.02076v1

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**Diagram 1:**
- **a)** Single-scatter event measurements
- **b)** Merged multiple-scatter event measurements

**Figure:**
- **Energy (keV):**
  - NESTv0.98, 180 V/cm
  - LUX (this work)

**Legend:**
- NEST: Single scatter
- NEST $^{83m}$Kr: 32.15 + 9.4 keV
- NEST $^{136}$Xe: 5.2 + 202.9 keV
- NEST $^{136}$Xe: 33.2 + 172.1 keV
- NEST $^{136}$Xe: 33.2 + 202.9 keV
- NEST $^{136m}$Xe: 196.6 + 39.6 keV
- NEST $^{137}$Xe: 33.2 + 375 keV
- NEST $^{137}$Xe: 33.2 + 202.9 + 172.1 keV
- LUX (this work)

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**Emission Peaks:**
- $^{83m}$Kr: 41.55 keV
- $^{131m}$Xe: 163.9 keV
- $^{127}$Xe & $^{129m}$Xe: 236.1 keV
- $^{208}$Tl & $^{214}$Bi: 583.2 keV & 609.3 keV
- $^{127}$Xe: 408.2 keV
- $^{127}$Xe: 208 keV

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**Percent Energy Resolution, $\sigma/\mu$:**
- LUX (this work), 180 V/cm
- Xe (2015), 1000 V/cm
- MiX (2015), 200 V/cm
- ZEPLIN-III (2012), 3900 V/cm
- XENON100 (2012), 530 V/cm
NR CALIBRATION WITH KINEMATICALLY-CONSTRAINED NEUTRON SCATTERS

D-D neutron generator outside of water tank
En=2.5 MeV

arXiv:1608.05381v1
NR CALIBRATION WITH KINEMATICALLY-
CONSTRAINED NEUTRON SCATTERS

\[ E_r = E_n \frac{4 m_n m_{Xe}}{(m_n + m_{Xe})^2} \frac{1 - \cos \theta}{2} \]
NR CALIBRATION WITH KINEMATICALLY-CONSTRAINED NEUTRON SCATTERS

\[ E_r = E_n \frac{4m_n m_{Xe}}{(m_n + m_{Xe})^2} \frac{1 - \cos \theta}{2} \]

Samuel Chan, Carlos Faham for the LUX Collaboration
NR CALIBRATION WITH KINEMATICALLY-CONSTRAINED NEUTRON SCATTERS

\[ E_r = E_n \frac{4m_n m_{X_e}}{(m_n + m_{X_e})^2} \left(1 - \cos \theta \right) \]
NR CALIBRATION WITH KINEMATICALLY-CONSTRAINED NEUTRON SCATTERS

\[ E_r = E_n \frac{4m_n m_X e}{(m_n + m_X)^2} \frac{1 - \cos \theta}{2} \]
NR CALIBRATION WITH KINEMATICALLY-CONSTRAINED NEUTRON SCATTERS

\[E_r = E_n \frac{4m_n m_{Xe}}{(m_n + m_{Xe})^2} \frac{1 - \cos \theta}{2}\]
NR CALIBRATION WITH KINEMATICALLY-CONSTRAINED NEUTRON SCATTERS

- S2 yield versus absolute energy measured to 0.7 keV (was 3 keV)
- S1 yield measured to ~1 keV via single scatters (was 3 keV)
NR YIELDS & DETECTION EFFICIENCY

- **Lindhard** fit (solid line)
  Lindhard 1963
  Fit as in Lenardo 2015

- **Bezrukov** fit (dashed line)
  Bezrukov 2011

- **Add $L y + Q y$ to obtain $\mathcal{L}$**

\[
E_{nr} = \mathcal{L}^{-1} \cdot (n_e + n_\gamma) \cdot W.
\]
\[
L = \frac{k \cdot g(\epsilon)}{1 + k \cdot g(\epsilon)}
\]

S2: 2 electrons emitted $\rightarrow$
S1: 2 photons detected $\rightarrow$
Events with S1+S2 $\rightarrow$
+ raw S2 cut $\rightarrow$
WHERE NEXT?

• Map out scintillation and ionisation yields down to \( \sim 0 \) keV
• Interesting physics is hiding below our threshold of a few keVr
• We run out of S1 but not S2 (still \( \sim 8 \) ionisations at 1 keVr)
• Remember challenge: must reach such energies in a large detector...

B-8 CNS SIGNAL MODEL

\( \frac{dE}{dE_R} + \)

FastNEST +

LZ Detector
Thank you!
COMING BACK TO NEST

- Detector-independent simulation framework – Physics of interactions in LXe
- Compatible with Geant4, integration into full simulations
- Stand-alone code for fast calculations (FastNEST). Coming soon
- You should use NEST if you want to generate a convincing signal model in liquid xenon

NEST is free and publicly available: [http://www.albany.edu/physics/NEST.shtml](http://www.albany.edu/physics/NEST.shtml) – see recent slides
NR model (LUX/NEST)

Charge production:

\[ n_e = L(E_0) \times \frac{E_0}{W} \left( \frac{1}{1 + N_{ex}/N_i} \right) (1 - r) + C \frac{n_{ph}}{f_l}(1 - f_l) \]

Light production:

\[ n_{ph} = L(E_0) \times \frac{E_0}{W} \left( 1 - \frac{1}{1 + N_{ex}/N_i} (1 - r) \right) \times f_l \]

Five free parameters:
- \( N_{ex}/N_i \)
- TIB (4 \( \zeta \))
- \( A \)
- \( k \) or \( \alpha \)
- \( C \)

NR signal loss:

\[ L = \frac{k \ g(\epsilon)}{1 + k \ g(\epsilon)} \quad \text{or} \quad \alpha \frac{s_e}{s_e + s_n} \]

Bi-excitonic quenching / ionization:

\[ f_l = \frac{1}{1 + A \ s_e} \]

Thomas-Imel recombination:

\[ r = 1 - \frac{\ln(1 + N_i \zeta)}{N_i \zeta} \]
SIGNAL MODEL: HEAVY WIMPS

dE/dE_R + FastNEST + LZ Detector
SIGNAL MODEL: B-8 NEUTRINOS (OR LIGHT WIMP)

dE/dE_R + FastNEST + LZ Detector
LZ SENSITIVITY

Requirement: $3 \times 10^{-48} \text{ cm}^2$ at 50 GeV
NR model (LUX/NEST)