Searching for Dark Matter with LZ

Hugh Lippincott, Fermilab for the LZ Collaboration

Exploring the Dark Universe
July, 2017
## LXe as Dark Matter Target

<table>
<thead>
<tr>
<th>Challenge</th>
<th>Solution</th>
<th>Liquid Xenon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extremely rare</td>
<td>Large mass</td>
<td>Very dense - 3 tonnes in 1 m³</td>
</tr>
<tr>
<td>Energy depositions of ~10 keV or below</td>
<td>Low energy thresholds</td>
<td>~60-70 electrons + photons / keV</td>
</tr>
<tr>
<td>Backgrounds - Impurities</td>
<td>Purification</td>
<td>Noble gases are (mostly) easy to purify</td>
</tr>
<tr>
<td>Backgrounds - Detector</td>
<td>Self shielding</td>
<td>Low MFP for ionizing radiation</td>
</tr>
<tr>
<td>Backgrounds - Internal/Detector</td>
<td>Discrimination</td>
<td>Charge to light ratio gives particle ID</td>
</tr>
</tbody>
</table>
Two phase Xenon Detectors

- Interaction in the xenon creates:
  - Scintillation light (~10 ns) - called S1
  - ionization electrons
- Electrons drift through electric field to liquid/gas surface
- Extracted into gas and accelerated creating proportional scintillation light - called S2
Two phase Xenon Detectors

- Excellent 3D reconstruction (~mm)
- Z position from S1-S2 timing
- XY position from hit pattern of S2 light
- Allows for self shielding, rejection of edge events
- Ratio of charge (S2) to light (S1) gives particle ID
- Better than 99.5% rejection of electron recoil (ER) events
Self shielding is powerful
Self shielding is powerful

- MeV gamma
- keV energy deposit
- MeV gamma

Must cross full volume without interacting
LUX <3×10^{-48} \text{ cm}^2

(XENON nT)
We performed a staged unblinding, starting with an ex- blinded (99% of ERs were accessible) until the event se- arch period. This did not result in changes in the event 

exposure of 4 live days distributed evenly throughout the 

We gratefully acknowledge support from the National 

Science Foundation, Swiss National Science Foundation, 

Planck Gesellschaft, Deutsche Forschungsgemeinschaft, 

actions, PITNGA-2011-289442), Fundacao para a Cien- 

era e a Tecnologia, Region des Pays de la Loire, Knut and 

Vatat, Initial Training Network Invisibles (Marie Curie 

The data is compatible in the likelihood analysis (Fig. 2c). None are within cS1 that are unavailable in this analysis.

ated for small S2s, near the 5 (out of 36) top edge PMTs 

limited position reconstruction resolution, especially lim-

losses near the wall. The inward reconstruction is due to 

Sixth and last, we add a small uniform background in 

log cS2

b

220

XENON1T (this work)

LUX (2017)

PandaX-II (2016)

XENON100 (2016)

More mass!

LUX - 100 kg (active)
PandaX-II - 329 kg (fid)
Xenon1T - 1 tonne (fid)
LZ = LUX + ZEPLIN

38 Institutions, 217 People

Black Hills State University
Brookhaven National Laboratory (BNL)
Brown University
Fermi National Accelerator Laboratory (FNAL)
Kavli Institute for Particle Astrophysics and Cosmology (KIPAC)
Lawrence Berkeley National Laboratory (LBNL)
Lawrence Livermore National Laboratory (LLNL)
Northwestern University
Pennsylvania State University
SLAC National Accelerator Laboratory
South Dakota School of Mines and Technology
South Dakota Science and Technology Authority (SDSTA)
STFC Rutherford Appleton Laboratory (RAL)
Texas A&M University
University at Albany (SUNY)
University of Alabama
University of California (UC), Berkeley
University of California (UC), Davis
University of California (UC), Santa Barbara
University of Maryland
University of Massachusetts

Center for Underground Physics (Korea)
Imperial College London (UK)
LIP Coimbra (Portugal)
MEPhI (Russia)
STFC Rutherford Appleton Laboratory (UK)
University College London (UK)
University of Bristol (UK)
SUPA, University of Edinburgh (UK)
University of Liverpool (UK)
University of Oxford (UK)
University of Sheffield (UK)
University of Maryland
University of Michigan
University of Rochester
University of South Dakota
University of Wisconsin-Madison
Washington University in St. Louis
Yale University
Collaboration meeting last week at SURF
Scale Up $\approx 50$ in Fiducial Mass

**LZ**

Total mass – 10 T  
WIMP Active Mass – 7 T  
WIMP Fiducial Mass – 5.6 T
Sanford Underground Research Facility

Davis Cavern 1480 m
(4200 mwe)
LUX Water Tank

LZ Here
LZ design notes

- More mass (x50 more than LUX, x6 more than Xenon1T)
- 494 3” PMTs on TPC
- Significant HV/grid engineering (no xenon experiment has achieved HV goals so far)
- Requirement: 50 kV  Goal: 100 kV
- Sophisticated veto system - maximizes fiducial volume
  - LXe “skin” - 93 1” PMTs + 38 2” PMTs
  - 120 outer detector PMTs
- Radioactivity, radioactivity, radioactivity!
System test at SLAC

- Main test platform for LZ
- Same cryogenics/control
- Phase I (ongoing)
- Full LZ fields in scaled prototype TPC
  - Can HV be achieved with sparking or light emission?
- Prototype circulation
- LZ architecture and compressor
- Phase II will test grids
Background suppression by screening

- Every component is screened and simulated for radioactivity
- E.g. cryostat made of the most radiopure titanium in the world: < 0.05 counts in 1000 days after cuts
- Similar campaign working with Hamamatsu on PMTs
- Backed up by extensive quality assurance during production
Background suppression by veto

- Two component outer detector
- Gd-loaded liquid scintillator
- Instrumented skin

Xe TPC only

Fiducial mass: 3.3 T

Xe TPC+skin

Fiducial mass: 4.2 T

TPC+skin+OD

Fiducial mass: 5.6 T
• Two component outer detector
• Gd-loaded liquid scintillator
• instrumented skin
• Xe TPC only
• Xe TPC+skin
• TPC+skin+OD

With veto, detector components are a subdominant background!

Fiducial mass: 3.3 T
Fiducial mass: 4.2 T
Fiducial mass: 5.6 T
Internal backgrounds

- Radon, Krypton, Argon
- Distributed throughout the liquid volume
- ER backgrounds (can discriminate, thankfully)
- Radon requirement (goal) of 20(1) mBq

Radon emanation measurements

Dust is a killer!
Internal backgrounds

• Contributes half our radon budget

• Emanation measurements of “clean room dust”

• Requirement of <500 ng/cm² of dust in LZ

  • Goal of 5 ng/cm²

  • SNO achieved 20 ng/cm², BOREXINO 1 ng/cm²

  • 1 gram total!

• Cleanliness protocols, witness plate protocols, packaging protocols

**Dust is a killer!**
### Background Estimates

<table>
<thead>
<tr>
<th>Component</th>
<th>Mass (kg)</th>
<th>Composite</th>
<th>U early (mBq/kg)</th>
<th>U late (mBq/kg)</th>
<th>Th early (mBq/kg)</th>
<th>Th late (mBq/kg)</th>
<th>Co60 (mBq/kg)</th>
<th>K40 (mBq/kg)</th>
<th>n/yr (inc. S.F. rej.)</th>
<th>ER (cts)</th>
<th>NR (cts) (w/ SF rej.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper PMT Structure</td>
<td>40.5</td>
<td>Y</td>
<td>3.90</td>
<td>0.23</td>
<td>0.49</td>
<td>0.38</td>
<td>0.00</td>
<td>1.46</td>
<td>2.53</td>
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<tr>
<td>Lower PMT Structure</td>
<td>69.9</td>
<td>Y</td>
<td>2.40</td>
<td>0.13</td>
<td>0.30</td>
<td>0.24</td>
<td>0.00</td>
<td>0.91</td>
<td>6.06</td>
<td>0.05</td>
<td>0.01</td>
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<tr>
<td>R11410 3&quot; PMTs</td>
<td>91.9</td>
<td>Y</td>
<td>71.63</td>
<td>3.20</td>
<td>3.12</td>
<td>2.99</td>
<td>2.82</td>
<td>15.41</td>
<td>81.83</td>
<td>1.46</td>
<td>0.013</td>
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<tr>
<td>R11410 PMT Bases</td>
<td>2.8</td>
<td>Y</td>
<td>287.74</td>
<td>75.80</td>
<td>28.36</td>
<td>27.93</td>
<td>1.43</td>
<td>69.39</td>
<td>34.65</td>
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<td>0.008</td>
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<td>R8520 Skin 1&quot; PMTs</td>
<td>6.1</td>
<td>Y</td>
<td>137.50</td>
<td>59.38</td>
<td>16.88</td>
<td>16.88</td>
<td>16.25</td>
<td>412.50</td>
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<td>0.2</td>
<td>Y</td>
<td>212.95</td>
<td>108.46</td>
<td>42.19</td>
<td>37.62</td>
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<td>123.61</td>
<td>3.62</td>
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<tr>
<td>Lower PMT Structure</td>
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<td>29.83</td>
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<td>3.15</td>
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<td>TPC PTFE</td>
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<td>0.02</td>
<td>0.03</td>
<td>0.03</td>
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<td>Grid Wires</td>
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<td>Field Shaping Rings</td>
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<td>TPC Thermometers</td>
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<td>335.50</td>
<td>90.46</td>
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<td>Xe Recirculation Tubing</td>
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<td>Y</td>
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<td>HV Conduits and Cables</td>
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<td>Y</td>
<td>1.9</td>
<td>2.0</td>
<td>0.5</td>
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<td>Cryostat Vessel</td>
<td>2406.1</td>
<td>N</td>
<td>1.59</td>
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<td>Cryostat Seals</td>
<td>33.7</td>
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<td>73.91</td>
<td>26.22</td>
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<td>10.03</td>
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<td>Cryostat Insulation</td>
<td>23.8</td>
<td>Y</td>
<td>18.91</td>
<td>18.91</td>
<td>3.45</td>
<td>3.45</td>
<td>1.97</td>
<td>51.65</td>
<td>69.83</td>
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<td>Cryostat Teflon Liner</td>
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<td>Outer Detector Tanks</td>
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<td>Y</td>
<td>0.16</td>
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<td>5.36</td>
<td>77.96</td>
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<td>Liquid Scintillator</td>
<td>17640.3</td>
<td>Y</td>
<td>0.1</td>
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<td>0.01</td>
<td>0.01</td>
<td>0.00</td>
<td>0.00</td>
<td>1.48</td>
<td>0.05</td>
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<td>Outer Detector PMTs</td>
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<td>570</td>
<td>470</td>
<td>395</td>
<td>388</td>
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<td>534</td>
<td>7,587</td>
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<td>Outer Detector PMT Supports</td>
<td>770.0</td>
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<td>1.20</td>
<td>0.27</td>
<td>0.33</td>
<td>0.49</td>
<td>1.60</td>
<td>0.40</td>
<td>14.30</td>
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<td><strong>Subtotal (Detector Components)</strong></td>
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<td><strong>6.20</strong></td>
<td><strong>0.070</strong></td>
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<tr>
<td><strong>222Rn (2.0 µBq/kg)</strong></td>
<td></td>
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<tr>
<td><strong>220Rn (0.1 µBq/kg)</strong></td>
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<tr>
<td><strong>natKr (0.015 ppt g/g)</strong></td>
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<tr>
<td><strong>natAr (0.45 ppb g/g)</strong></td>
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<tr>
<td><strong>210Bi (0.1 µBq/kg)</strong></td>
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<tr>
<td><strong>Laboratory and Cosmogenics</strong></td>
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<td></td>
<td>4.3</td>
<td>0.06</td>
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<td><strong>Fixed Surface Contamination</strong></td>
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<tr>
<td><strong>Subtotal (Non-ν counts)</strong></td>
<td></td>
<td></td>
<td><strong>921</strong></td>
<td><strong>0.50</strong></td>
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<td></td>
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</table>

### Physics Backgrounds

<table>
<thead>
<tr>
<th>Component</th>
<th>Count Rate (cts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>136Xe 2νββ</td>
<td>67</td>
</tr>
<tr>
<td>Astrophysical ν counts (pp+7Be+13N)</td>
<td>255</td>
</tr>
<tr>
<td>Astrophysical ν counts (8B)</td>
<td>0</td>
</tr>
<tr>
<td>Astrophysical ν counts (Hep)</td>
<td>0</td>
</tr>
<tr>
<td>Astrophysical ν counts (diffuse supernova)</td>
<td>0</td>
</tr>
<tr>
<td>Astrophysical ν counts (atmospheric)</td>
<td>0</td>
</tr>
<tr>
<td><strong>Subtotal (Physics backgrounds)</strong></td>
<td><strong>322</strong></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1.240</strong></td>
</tr>
<tr>
<td><strong>Total (with 99.5% ER discrimination, 50% NR efficiency)</strong></td>
<td><strong>6.22</strong></td>
</tr>
</tbody>
</table>

**My summary of the summary table**

6 ER, 0.6 NR in 1000 days!
### Backgrounds summary

<table>
<thead>
<tr>
<th>Subtotal (Non-ν counts)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Physics Backgrounds</td>
<td></td>
</tr>
<tr>
<td>136Xe 2νββ</td>
<td></td>
</tr>
<tr>
<td>Astrophysical ν counts (pp+7Be+13N)</td>
<td></td>
</tr>
<tr>
<td>Astrophysical ν counts (8B)</td>
<td></td>
</tr>
<tr>
<td>Astrophysical ν counts (Hep)</td>
<td></td>
</tr>
<tr>
<td>Astrophysical ν counts (diffuse supernova)</td>
<td></td>
</tr>
<tr>
<td>Astrophysical ν counts (atmospheric)</td>
<td></td>
</tr>
<tr>
<td>Subtotal (Physics backgrounds)</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td></td>
</tr>
<tr>
<td>Total (with 99.5% ER discrimination, 50% NR efficiency)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>921</th>
<th>0.50</th>
</tr>
</thead>
<tbody>
<tr>
<td>67</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>255</td>
<td>0</td>
<td>0**</td>
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<tr>
<td>0</td>
<td>0.21</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>0.46</td>
<td></td>
</tr>
</tbody>
</table>

- Lots of neutrinos - significant fraction of both ER and NR counts
- Discrimination cuts are important

My summary of the summary table: 6 ER, 0.6 NR in 1000 days!
Sensitivity projections

<table>
<thead>
<tr>
<th>Detector Parameter</th>
<th>Reduced</th>
<th>Baseline</th>
<th>Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light collection (PDE)</td>
<td>0.05</td>
<td>0.075</td>
<td>0.12</td>
</tr>
<tr>
<td>Drift field (V/cm)</td>
<td>160</td>
<td>310</td>
<td>650</td>
</tr>
<tr>
<td>Electron lifetime (μs)</td>
<td>850</td>
<td>850</td>
<td>2800</td>
</tr>
<tr>
<td>PMT phe detection</td>
<td>0.8</td>
<td>0.9</td>
<td>1.0</td>
</tr>
<tr>
<td>N-fold trigger coincidence</td>
<td>4</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>$^{222}$Rn (mBq in active region)</td>
<td>13.4</td>
<td>13.4</td>
<td>0.67</td>
</tr>
<tr>
<td>Live days</td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
</tr>
</tbody>
</table>

- ~6 keVnr threshold in baseline scenario (LUX achieved 4.5 keVnr)
- Driven by S1 trigger coincidence threshold
- Better than 99.5% ER/NR discrimination at this field
Sensitivity projections (1000 days)

- LZ 90%CL Median (Baseline)
- LZ 90%CL Median (Goal)
- CMSSM (1σ)
- CMSSM (2σ)

- Zeplin-III (2011)
- PandaX (2016)
- LUX WS2013+WS2014-16
- XENON1T (2017)

- ~7 8B events
- ~700 8B events

@40 GeV: 2.3e-48 Nominal
1.1e-48 Goal
WIMP signal region

- 40 GeV WIMP
- 1σ
- 2σ
Sensitivity projections (1000 days)

LZ projected
- 5\(\sigma\) Median Significance
- 3\(\sigma\) Median Significance
- 90\% CL Median (Baseline)
- XENON1T 90\% CL

\(\log_{10}(\sigma_{SI}^N)[pb]\)

\(\sigma_{SI}^N[cm^2]\)

\(\nu-N\) coherent scattering

1 event

3\(\sigma\) significance 1000 tonne-years
Schedule

- 2012 - LZ Collaboration formed
- 2014 - LZ Project start
- 2015 - DOE CD-1 approval - Conceptual Design Report (1509.02910)
- 2016 - DOE CD-3 approval - Technical Design Report (1703.09144)
- March 2017 - LUX removed from water tank
- 2018 - Underground construction begins
- 2019 - Commissioning
Schedule

• Competition is fierce!
• XENON1T out with new results, already heading to XENONnT
  • Infrastructure already in place - update of TPC and cryostat
• PandaX also has a strong group
• We’re moving as fast as we can!
Summary

- Liquid xenon TPCs are the leading technology in the search for ~10 GeV and above WIMPs (spin independent)
- Mature technology, challenge is to make the detectors bigger
- Scaling up raises new technical questions (HV, internal radioactivity, …)
- LZ is poised to achieve a factor >30 more sensitivity than current best limits
- The race is on for the next order of magnitude in sensitivity
WIMP Mass [GeV/c^2]

WIMP–nucleon cross section [cm^2]

SuperCDMS Soudan Low Threshold
XENON 10 S2 (2013)
CDMS-II Ge Low Threshold (2011)

CDMSlite (2013)
CoGeNT (2012)
CDMS Si (2013)
SIMPLE (2012)
COUPP (2012)
ZEPLIN-III (2012)
CDMS II Ge (2009)
Xenon100 (2012)
EDELWEISS (2011)
CRESST

7Be Neutrinos
Neutrinos

NEUTRINO COHERENT SCATTERING
Atmospheric and DSNB Neutrinos

CDMSlite
SuperCDMS SNOLAB
LUX 300-day
LUX (2013)
DarkSide 50
DEAP3600
SuperCDMS SNOLAB
PICO250-CF3I
PICO250-C3F8
LZ

DEAP3600
PICO250-CF3I
PICO250-C3F8
LZ

CDMSlite
SuperCDMS SNOLAB
DarkSide G2
DarkSide 50
LUX (2013)
DEAP3600
SuperCDMS SNOLAB
PICO250-CF3I
PICO250-C3F8
LZ

DEAP3600
PICO250-CF3I
PICO250-C3F8
LZ
Dark Matter Searches: Past, Present & Future

DM Direct Search Progress Over Time (2012)

~1 event kg\(^{-1}\) day\(^{-1}\)

(Gross Masses kg)

~1 event 100 kg\(^{-1}\) yr\(^{-1}\)

~1 event 1 tonne\(^{-1}\) yr\(^{-1}\)

σ=2 \times 10^{-48} \text{ LZ 7t}
Some LXe physics

Electron/Nuclear recoil

Excitation

Ionisation

$\text{Xe}^*$

$\text{Xe}^+$

$\text{Xe}_2^*$

$\text{Xe}_2^{**}$

$+\text{Xe}$

$+\text{e}^-$ (recombination)

$2\text{Xe}$

$2\text{Xe}$

$\text{Xe}^{**} + \text{Xe}$

178nm

Triplet 27ns

Singlet 3ns

178nm

$= 178 \text{ nm}$

Transparency of the medium to its own scintillation light, i.e. the energy of the emitted photons is less than the energy difference between the ground state (of the two separated atoms) and the first atomic excited state ensures good light collection.

Regions without the need for any physical barriers. Comprehensive overviews of the properties of liquid xenon and its utilisation in noble gas detectors are given in Refs. [72, 83].

4.2.1 The primary scintillation signal

The scintillation light produced in a particle interaction within the liquid xenon is attributed to two separate processes involving excited atoms and ions. A flow chart of the individual processes, both resulting in the production of VUV scintillation photons and their interconnection, is shown in Fig. 4.7 [126, 127].

Firstly, direct excitation takes place resulting in excitation luminescence by the de-excitation of singlet and triplet states of the created excimer Xe$^\ast_2$, see Eq. (4.3). The transition of the excited states occurs at short interatomic distance, where the ground state potential is repulsive and the molecule becomes dissociated. The two possible de-excitations from the lowest electronic excited states are quite different in their characteristic decay time due to the forbidden direct transition of the triplet to the ground state. The latter becomes possible through spin-orbital coupling and the...
Some LXe physics

- Significant difference between ER and NR tracks
- ER lead to more signal than NR
- More NR energy goes into heat and is lost
- Lindhard factor, $L_{\text{eff}}$, Quenching factor
- Two energy scales $\text{keV}_{\text{ee}}$ and $\text{keV}_{\text{nr}}$
- Leads to different behavior with field
- Also leads to ER/NR discrimination

Figure 6.1: Example electron recoil tracks at 4, 10, 20, and 40 keVee, simulated using Penelope. Each blue dot is one xenon ion, and the red X marks the location of the initial recoil. The boxes correspond to the box sizes ($a_i$) in uncombined model, as listed in Table 6.2.

6.3.2 Nuclear recoil track Monte Carlo

For nuclear recoils, the Monte Carlo program SRIM/TRIM [88] creates cascades of recoils using the universal nuclear scattering cross sections given by Ziegler [99]. Although this program does keep track of energy lost via electronic channels, it is difficult to extract this information from the output available to the user. We therefore create a Monte Carlo to suit our purposes, dubbed RIVAL (Recoiling Ions in Various Atomic Liquids). This program also generates nuclear recoil tracks, following the primary and daughter recoils down to a set energy threshold and keeping track of energy lost via low-energy nuclear collisions and electronic stopping along the way. It turns out that the details of the nuclear recoil simulation are unimportant in our recombination model, but see Appendix C for a complete description of the Monte Carlo.

Sample nuclear recoil tracks are shown in Fig. 6.3. As with electron recoils, hard scatters give the track a tree-like structure. Since stopping power in nuclear recoils decreases as energy is lost, such branches have the opposite effect on ionization density as in electron recoils — every branch ends in a sparse scattering of ions. Figure 6.2 shows the rms radii of nuclear recoil tracks as a function of energy.
Requires calibration

- LUX has really done great work here
- Kr-83m - Over 1e6 events spread uniformly throughout detector

Fiducial volume determination

Position-based S1 corrections
Requires calibration

- LUX has really done great work here
- Tritiated methane (CH\textsubscript{3}T) - to measure low energy ER band

Low energy ER

Measured in both light and charge
Requires calibration

- LUX has really done great work here
- DD neutron generator to measure NR yields

![Diagram showing drift time vs. y coordinate](image)

**Drift time [µs]**: 
- 0 to 200

**y' [cm]**: 
- 0 to 50

**log(Φ(A/S) / 6.4 µs / 1.0 cm)**: 
- -1 to 1.5

**2.45 MeV neutrons provided via conduit extending through water tank**

**TPC in center of 8 m diameter water tank**

**Top S2 hit pattern: x-y position**

**S1[y'_1]** + **S1[y'_2]**

**S2[y'_1]** vs. **S2[y'_2]**

**Δt**: 2 separation

**Δt**: Drift time

**x**: Drift direction

**y**: Position along the beam pipe axis

**θ**: Angle from the beam line

**x'**: Drift direction in the TPC

**y'**: Distance from the liquid surface

**T**: Total energy of the event

**Q**: Energy of the nuclear recoil

**S1**: Signal size from the PMT arrays

**S2**: Signal size from the LUX TPC

**NR**: Nuclear recoil band

**D-D**: Deuterium-deuterium

**D**: Distance from the source to the TPC

**L**: Length of the water tank

**WIMP**: Weakly interacting massive particle

**Homogeneous**: Uniform distribution

**Gaussian**: Normal distribution

**CC**: Charged current

**NC**: Neutral current

**NR**: Nuclear recoil

**S**: Sensitivity

**S1**: First signal

**S2**: Second signal

**x**: Position along the beam pipe axis

**y**: Distance from the liquid surface

**z**: Depth in the TPC

**S1** and **S2** are used for each section.

The energy spectrum of the specific DD108 hardware is characterized at Brown University prior to use in the LUX calibration. The coordinate system is transverse to the beam pipe axis in the horizontal plane.

The coordinate system is defined here. The orientation of the Cartesian coordinate system is along the beam pipe direction with zero at the point of the beam. The source of neutron production inside the monolithic liquid xenon target is characterized at Brown University prior to use in the LUX calibration.
• LUX has really done great work here
• DD neutron generator to measure NR yields

![Graph showing ionization signal vs. nuclear recoil energy]

- Requires calibration
- Sys. uncertainty due to position reconstruction energy bias correction
-Sys. uncertainty due to $S_2$ corrections, $g_2$, and neutron source energy spectrum

FIG. 3. The gray points represent the measured ionization signal for each of the 1031 events remaining after all cuts in the double-scatter dataset. The gold crosses illustrate the signal dependence as a function of the energy deposited by the recoils before other cuts are applied and has a constant efficiency across the energy range.
Leads to background rejection

Grey contours indicate lines of constant energy
Some LXe physics

Chapter 4. The ZEPLIN–III Experiment

Figure 4.7: Flowchart of the two processes creating a primary scintillation signal in an elastic recoil in liquid xenon. In the primary interaction both excited and ionised Xe atoms are created. The two branches produce, in their final stages, excited dimer states responsible for the typical scintillation light of the noble gas ($\lambda = 178$ nm). Transparency of the medium to its own scintillation light, i.e. the energy of the emitted photons is less than the energy difference between the ground state (of the two separated atoms) and the first atomic excited state, ensures good light collection.

4.2.1 The primary scintillation signal

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For 122 keV ER, 56 keV NR
$\sigma LUX (2015) \quad LUX 332d (2016) \quad Zeplin-III (2011) \quad LZ projected$

- $90\%$ CL Median (Baseline - 1000 days)
- $90\%$ CL Median (Baseline - 3000 days)
- $90\%$ CL Median (Goal - 1000 days)
- $90\%$ CL Median (Goal - 3000 days)

$v-N$ coherent scattering

$v-N$ coherent, 3$\sigma$ significance

1000 Tonne-years
LZ 90% CL
Reduced
Baseline
Goal
Rn-222 content

- 5x, 67 mBq
- Baseline, 13.4 mBq
- 0.05x, 0.67 mBq
PLR (Profile Likelihood Ratio)

- Simple fiducial of 5600 kg (X,Y,Z position info not yet implemented in PLR)
- Dominant ER: Rn, Kr, pp-neutrinos spatially uniform like signal