Final Results from Zeplin-III at Boulby

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Imperial College London (UK)
ITEP-Moscow (Russia)
LIP-Coimbra (Portugal)
Rutherford Appleton Laboratory (UK)

DARK MATTER SILVER JUBILEE 2012
Pacific Northwest National Laboratory
June 19-21, 2012
ZEPLIN-III XENON EMISSION DETECTOR

- Time projection chamber with 12 kg of active liquid xenon
- Readout of scintillation (S1) and ionisation (S2) with array of 31 PMTs
- Strong electric field (~4 kV/cm), planar design, no extraction grids
- Construction from low background, xenon-friendly materials
SINGLE ELECTRON EMISSION STUDIES

• Single electrons released in LXe detected with excellent S/N ratio
  – Ultimate sensitivity in ionisation channel
  – Absolute calibration of ionisation and electroluminescence yields
  – Determination of free electron lifetime in the LXe using only WIMP search data
  – Ionisation spectrometer working below S1 threshold
    (interesting for light WIMP searches, coherent neutrino scattering)

S1 S2
SE

Electron lifetime in LXe obtained from dark data
(comparison with Co-57 measurements)

Santos et al., JHEP 12 (2011) 115
Edwards et al., Astropart. Phys. 30: (2009) 54
BOULBY UNDERGROUND LABORATORY

Underground Research Laboratory
Boulby
BOULBY SCIENCE RUNS

- **First science run (FSR) at Boulby**: 83 days in 2008
  Strong constraints on WIMP-nucleon scattering XS

- **Phase-II upgrades commissioned in 2009/10**
  - New photomultiplier array (ultra-low background)
  - New anti-coincidence veto (bk reduction, diagnostic)
  - New calibration hardware (reduction of systematics)
  - System automation (improved stability, underground effort)

- **Second science run (SSR) 23 June 2010 to 7 May 2011**
  Longest run of any noble liquid WIMP detector (319 days)
  Effective fiducial exposure ~560 kg*days (4x FSR)
UPGRADES: NEW PMT ARRAY AND VETO

- PMT $\gamma$-rays limited sensitivity of first run by a large factor
- New PMT model developed with manufacturers (ETEL)
- 20-fold reduction in $\gamma$-ray activity, but poor optical performance
- 52-module neutron veto installed around WIMP target
- Gd-loaded polypropylene surrounded by 1t of plastic scintillator
- 60% neutron efficiency, diagnostic tool

Assembly of bespoke low-background PMTs

Ghag et al. (2011), Astropart. Phys. 35: 76
Akimov et al. (2010), Astropart. Phys. 34: 151
SSR BACKGROUNDS

- Good (absolute) agreement with Monte Carlo predictions from (sub-)component radio-assays
- Gamma background reduced 18x (<1 dru) (expectation <1 evt assuming FSR discrimination)
- Neutron background reduced 30x (expectation <1 evt after veto & efficiencies)

Electron and nuclear recoil background rates
(5-50 keVnr in 6.5 kg fiducial, unity signal acceptance, before veto)

<table>
<thead>
<tr>
<th>Material</th>
<th>mass, kg</th>
<th>e-recoil, dru</th>
<th>ptag</th>
<th>n/year</th>
<th>dtag</th>
</tr>
</thead>
<tbody>
<tr>
<td>Krypton-85</td>
<td>12.5</td>
<td>(&lt;0.1)</td>
<td>~0</td>
<td>~1</td>
<td>~1</td>
</tr>
<tr>
<td>Ceramic feedthroughs</td>
<td>0.9</td>
<td>0.08</td>
<td>0.30</td>
<td>1.35</td>
<td>0.58</td>
</tr>
<tr>
<td>Photomultipliers</td>
<td>4.2</td>
<td>0.40</td>
<td>0.26</td>
<td>0.74</td>
<td>0.58</td>
</tr>
<tr>
<td>Rock (halite)</td>
<td>~0</td>
<td>~0</td>
<td>~0</td>
<td>~0.53</td>
<td>0.58</td>
</tr>
<tr>
<td>Polypropylene shield</td>
<td>1,266</td>
<td>0.25</td>
<td>0.04</td>
<td>0.10</td>
<td>0.58</td>
</tr>
<tr>
<td>Scintillator modules</td>
<td>1,057</td>
<td>0.09</td>
<td>~1</td>
<td>~0.03</td>
<td>~1</td>
</tr>
<tr>
<td>Copperware</td>
<td>~400</td>
<td>(&lt;0.1)</td>
<td>0.10</td>
<td>(~0.15)</td>
<td>0.58</td>
</tr>
<tr>
<td>Lead castle</td>
<td>~60,000</td>
<td>0.01</td>
<td>0.54</td>
<td>~0</td>
<td>0.58</td>
</tr>
<tr>
<td>Radon-222</td>
<td>(1 m³?)</td>
<td>0.03</td>
<td>0.19</td>
<td>~0</td>
<td>–</td>
</tr>
<tr>
<td>Muon-induced</td>
<td>~0.3</td>
<td>~0.3</td>
<td>~1</td>
<td>~1</td>
<td>~1</td>
</tr>
<tr>
<td>SSR total</td>
<td>0.36±0.05</td>
<td>0.28</td>
<td>3.05±0.5</td>
<td>0.58</td>
<td></td>
</tr>
<tr>
<td>SSR data</td>
<td>0.75±0.05</td>
<td>0.28</td>
<td>n/a</td>
<td>~1</td>
<td></td>
</tr>
<tr>
<td>(FSR [6])</td>
<td>14.5±0.5</td>
<td>–</td>
<td>(36±18)*</td>
<td>–</td>
<td></td>
</tr>
</tbody>
</table>
MERCURY VERTEX RECONSTRUCTION

- Reconstruction of (x, y, E) separately for the two responses (z from drift time)
  
  S2 using weighted least squares
  \[ \chi^2(r, N) = \sum_i w_i(r, N) (N \eta_i(r) q_{si} - A_i)^2 \]
  
  S1 using maximum likelihood fit
  \[ \ln L(r, N) = \sum_i (n_i \ln(N \eta_i(r)) - N \eta_i(r)) + C \]

\[ \eta_i(r) \rightarrow \text{PMT (cylindrical) Light Response Functions} \]

Solovov et al., arXiv:1112.1481

Figure 3. Iterative reconstruction of the LRFs from $^{57}$Co calibration data. The top row: the evolution of the distribution of estimated event positions from S2 pulses. The bottom row: the response of PMT 11 (with centre at (-79.5, -45.9)) versus estimated distance from its centre (dots) and the corresponding S2 LRFs derived from these distributions (curve). a) Initial position estimates obtained by centroid. b) First iteration. c) Final (5-th) iteration.
MERCURY PERFORMANCE

- Simultaneous fit of S1 and S2 signals to 31 PMT light response functions; common cylindrical functions found for all channels.
- Iterative process to obtain LRFs also ‘flat-fields’ the array.
- Reconstruction for 122 keV $\gamma$-rays in central region:
  \[ \text{S1: 13 mm, S2: 1.6 mm, } E (\alpha S1 + \beta S2) = 8.3\% \text{ (all FWHM)} \]
- Multiple scintillation, single ionisation events (‘living-dead’)

Spatial ML/$\chi^2$ maps help identify multiple vertices.

Mercury spatial maps

- Co-57 gamma-rays

$\sigma_y = 1.6 \text{ mm (FWHM)}$

$\sigma_{E^*} = 8.3\% \text{ (FWHM)}$
SSR WIMP SEARCH RESULTS

- Veto prompt tags (in green) – mostly gamma-rays (28% of electron recoils)
- Lower $\gamma$-ray background than FSR, but poorer discrimination (1:280 v 1:7800)
- Veto delayed tags (in red) consistent with predicted 0.7% accidentals rate
- Negligible neutron background confirmed (e.g. no tags below NR median)
- 8 candidate events in acceptance region (7-29 keVr, 2-45% acceptance)
NEUTRON BACKGROUND – DATA

**BACKGROUND EXPECTATIONS IN SSR DATASET**

<table>
<thead>
<tr>
<th>NEUTRONS</th>
<th>E-RECOILS</th>
</tr>
</thead>
<tbody>
<tr>
<td>total in 7-28 keVr</td>
<td>0.79 rate, evt/kg/day/keVee 0.75</td>
</tr>
<tr>
<td>total in 2-12 keVee</td>
<td>10080</td>
</tr>
<tr>
<td>efficiencies</td>
<td>44% 0.35 efficiencies 39% 3931</td>
</tr>
<tr>
<td>acceptance</td>
<td>43% 0.15 veto a/c 72% 2830</td>
</tr>
<tr>
<td>veto a/c</td>
<td>40% 0.06 discrimination* 1:7,800 0.4</td>
</tr>
</tbody>
</table>

**0.06 un-vetoed neutron events** predicted for WIMP search region in SSR dataset (neutron rate published ahead of WIMP analysis)

**Rate of accidental veto coincidences in delayed tag is** (0.6±0.05)%

**Single delayed tag in [μ−2σ, μ+σ] sets limit of 0.75 neutron events in box** at 90% CL

**Neutron background successfully mitigated**
Skew-Gaussian distribution of ER band confirmed with vetoed events in dark data and with Cs-137 calibration data

Fitting in 2 keVee bins: $6.5 \pm 2.4$ events

Cs-137 calibration data: $9 \pm 3$ events
1. **Partitioning of signal box to optimise sensitivity**

   MC from SG shape for $\gamma$ background above box with 2-bin Feldman-Cousins (no data involved)

   Optimal partition at 24% acceptance:

   Then consider SSR data: 7+1 events

2. **Profile Likelihood Ratio test statistic**

   Likelihood ratio distribution studied with MC to ensure correct coverage

   $$\mathcal{L}(\mu, \beta) = \mathcal{L}_{\text{box}}(\mu, \beta) \cdot \mathcal{L}_{\text{Cs}}(\beta) \cdot \mathcal{L}_{\text{extrap.}}(\beta)$$
WIMP-NUCLEON ELASTIC XS LIMITS

SPIN-INDEPENDENT

SPIN-DEPENDENT WIMP-NEUTRON

NEW METHOD OF REGISTRATION OF IONIZING-PARTICLE TRACKS IN CONDENSED MATTER\textsuperscript{1)}

B.A. Dolgoshein, V.N. Lebedenko, and B.U. Rodionov
Moscow Engineering Physics Institute
Submitted 14 April 1970
ZhETF Pis. Red. 11, No. 11, 513 – 516 (5 June 1970)

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Vadim Nikolaevitch Lebedenko
11/10/1939 – 11/05/2008

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E. Santos et al., Single electron emission in two-phase xenon […] coherent neutrino-nucleus scattering, JHEP12 (2011) 115
L. Reichhart et al., Quenching factor for low energy nuclear recoils in a plastic scintillator, Submitted to Phys. Rev. C (2011)
F. Neves et al., ZE3RA: the ZEPLIN-III reduction and analysis package, JINST 6, P10004 (2011)

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THE END OF ZEPLIN AT BOULBY
NEAR-JUBILEE OF DM SEARCHES IN THE UK

- UK Dark Matter Collaboration started by P. F. Smith (RAL) in 1987
- Exploring cryogenic bolometers, sodium iodide, gaseous TPC, liquid xenon
- 3 decades in sensitivity achieved with only ~10-fold increase in target mass
ZEPLIN → LUX350 → LUX-ZEPLIN

LUX350

LUX testing Sanford Lab

Davis Complex Homestake

LZ: 7 tonne LXe target
THANK YOU
ADDITIONAL SLIDES
SCINTILLATION AND IONISATION YIELDS IN LXE

- Results with two PMT arrays from data/MC comparison method (calibrated Am-Be sources)
- Agreement with recent beam measurements: gentle decrease of $L_{\text{eff}}$ to lower energies
- New results also for ionisation yield, in general agreement with beam data

FIG. 3. The energy-dependent relative scintillation yield for nuclear recoils $L_{\text{eff}}$ (solid lines) for the two ZEPLIN–III datasets, including relevant 68% C.L. bands (FSR: green $\nabla$, SSR: blue $\nabla\nabla$). Below the analysis range (corresponding to $\sim 7 - 9\text{ keV}_{nr}$), the scintillation yield is indicated as dashed lines. Also shown are previous published measurements using mono-energetic neutron beams: (●)[10], (■)[11], (▲)[12], (◇)[25], (△)[26], (▽)[27] and (◇) [21], or obtained using a similar Monte Carlo matching procedure (▽)[7].

FIG. 5. The ionisation yield $Q_\gamma$ for nuclear recoils as derived from the FSR (green $\nabla$) and SSR (blue $\nabla\nabla$) datasets including relevant 68% C.L. bands. Results below the analysis range are indicated by dashed lines. Also shown are previous measurements at 1.0 kV/cm (●) and 4.0 kV/cm (■) from Ref. [11], at 2 kV/cm (□), (△), 0.3 kV/cm (◇) and 0.1 kV/cm (◇) from Ref. [21] and spectra obtained using similar Monte Carlo matching procedures at 0.73 kV/cm (▲) [7] and (▽) [28].
SCINTILLATION AND IONISATION YIELDS IN LXE

- $L_{\text{eff}}$ results also from new method going ‘sub-threshold’ in S1 (assuming ionisation yield)
- S1 is any light that precedes S2 (but subtract light with non-physical drift times)

Fig. 7. The relative scintillation yield for nuclear recoils $L_{\text{eff}}$ as determined by extending the event selection to S2-only events for the SSR Am–Be data. Also shown are the results obtained using the Monte Carlo fitting method, as in Fig. 3.
Accurate measurement of all SERs may not be possible, but understanding signals at this level is essential for WIMP searches!

Developed *in situ* calibration method using actual data; No knowledge of SER required, Exact measurement conditions

- SER mean & width, plus channel linearity and integration offset in few-photon regime for all PMTs
DATA CORRECTIONS

Detector tilt
Mean correction ±1.9%

GXe pressure
Mean correction ±1.1%

Electronic gain
Mean correction ±4.7%

Polar variation of S2 pulse width

Traditional lifetime measurement

Electron lifetime
Mean correction +37% (fiducial average)
SIGNAL ACCEPTANCE

Am-Be neutron calibration

2-3 keVee

10-12 keVee

H. Araújo