Low energy calibration of liquid xenon detectors

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Outline

1. Introduction
2. Scattering of dark matter particles off nuclei...
3. ... and off electrons
Motivation

After Planck: 26.8% of the Universe is made of Dark Matter

→ Astronomical evidences:
  Star rotation curves,
  Gravitational lensing, Galaxy clusters ...

Most general theoretical approach:

WIMP
(Weakly Interacting Massive Particle)

A different possibility:

Light DM particle
(such that it scatters off electrons)
Direct dark matter detection

Light DM particle

WIMP

Detection via elastic scattering off

nuclei → nuclear recoils

electrons → electronic recoils
Detector response and discrimination
Two phase xenon TPC

- Scintillation signal (S1)
- Proportional signal (S2)

Electronic/nuclear recoil discrimination

- Energy scales for NR and ER based on S1!
- Quenching processes are different for NR and ER
The XENON100 experiment

- International collaboration
- 30 cm length and 30 cm ∅
- 161 kg LXe (30 – 50 kg fiducial mass)
- Selected very low radioactivity materials

Located at LNGS underground lab (Italy)
**XENON100: discrimination**

- **Electronic recoil band**: defined with $^{60}\text{Co}$ and $^{232}\text{Th}$ sources
- **Nuclear recoil band**: defined with AmBe neutron source

**S1**: number of photoelectrons detected by the photosensors (corrected for spatial light collection variations)

**keV$_{nr}$**: derived energy scale
**Introduction**

**$L_{\text{eff}}$ direct measurements**

Nuclear recoil energy ($E_{nr}$):

$$E_{nr} = \frac{S_1}{L_y L_{\text{eff}}} \times \frac{S_e}{S_r}$$

- $S_1$: measured signal in p.e.
- $L_y$: $LY$ for 122 keV $\gamma$ in PE/keV
- $S_e/S_r$: quenching for 122 keV $\gamma$/NR due to drift field

$L_{\text{eff}} = q_{\text{nucl}} \times q_{\text{el}} \times q_{\text{esc}}$

![Graph with data points and lines representing $L_{\text{eff}}$ vs. Energy [keVnr]](image-url)
Results from 225 live days data (2012)

Science data

- Background expectation in the benchmark region:
  \((1.0 \pm 0.2)\) events

\[ \rightarrow \] Exclusion limit derived using profile likelihood method
Result of a direct DM detection experiment

→ Statistical significance of signal over expected background?

- **Positive signal**
  - Region in $\sigma_\chi$ versus $m_\chi$

- **Zero signal**
  - Exclusion of a parameter region
    - Low WIMP masses: detector threshold matters
    - Minimum of the curve: depends on target nuclei
    - High WIMP masses: exposure matters
      \[ \epsilon = m \times t \]
Results from XENON100

Spin-independent:
\[2 \times 10^{-45} \text{ cm}^2 \text{ at } 55 \text{ GeV/c}^2\]
WIMP mass


Spin-dependent:
\[3.5 \times 10^{-40} \text{ cm}^2 \text{ at } 45 \text{ GeV/c}^2\]
WIMP mass

\[XENON100, \text{ arXiv:1301.6620}\]
Verification of nuclear recoil energy scale

Monte Carlo simulation of neutron source
XENON100, arXiv:1304.1427 (work of M. Weber (MPIK))

- Input AmBe spectrum (ISO 8529-1 standard). Analysis robust against variations of this spectrum
- Source strength measured at the German Metrology Institute (PTB) $160 \pm 4$ n/s
- Complete Monte Carlo description of the detector including detector shield (water, lead, polyethylene and copper)
- $E_{\text{dep}}$ is converted to $S1$ and $S2$ including thresholds, resolutions and acceptances from data
MC simulation of neutron source

- Step 1: Using $L_{\text{eff}}$ from direct measurements, reproduce S2 spectrum $\rightarrow$ obtain optimum $Q_y$

- Step 2: Using the obtained $Q_y$, reproduce S1 spectrum $\rightarrow$ obtain a new $L_{\text{eff}}$

Best fit of source strength: 159 n/s
MC simulation of neutron source

- Poor agreement below 2 PE due to unknown efficiencies below threshold
- Good overall agreement. Best fit $L_{\text{eff}}$ matches previous measurements

→ Results of XENON100 remain unchanged using this $L_{\text{eff}}$
Recent results from CDMS

CDMS Si results from April 15th
140 kg-day exposure
3 events detected (0.7 expected)

Likelihood analysis: 0.19% probability that the known-background-only hypothesis

- Best fit at $1.9 \times 10^{-41}$ cm$^2$ at 8.6 GeV/c$^2$ WIMP mass

CDMS, arXiv: 1304.4279
How would CDMS signal look in XENON100?

Event distribution that XENON100 would observe for \( \sigma = 1.9 \times 10^{-41} \text{ cm}^2 \) and 8.6 GeV/c\(^2\) WIMP mass.
A different signature of dark matter

DAMA annual modulation

- Ultra radio-pure NaI crystals
- Annual modulation of the background rate in the energy region \((2 - 5)\, \text{keV}\)
- What if the DM particle scatters off electrons?

Calibration data in XENON100

Electronic recoil region:
energy calibration necessary

Nuclear recoil calibration
provides inelastic mono-energetic
lines and metastable states: 40, 80, 164 and 236 keV
Calibration using $^{83m}$Kr

$^{83m}$Kr calibration source:
- EC decay-product of $^{83}$Rb
- Lines at 9.4 and 32.1 keV
- Uniform distribution

$^{83m}$Kr (9.4 keV) $^{32}$ keV line $^{6}$ pe/keV, $^{9.4}$ keV line $^{20}$% $^{6.35}$ pe/keV,

Target mass: $\sim$ 0.1 kg LXe
Volume: 3 cm drift length and 3.5 cm diameter
Two R9869 PMTs
6 pe/keV in double phase
→ at University of Zürich

A. Manalasay et al., Rev. Sci. Instr. 81, 073303 (2010), 0908.0616
Compton measurement: low energy electron recoils

Determination of LXe light yield at small scattering angles → electron energies down to $\sim 1.5$ keV

Setup:
- $\gamma$-rays from a $^{137}$Cs source
- Energies $< 9.4$ keV → $< 8.5^\circ$ scattering angle
- Goniometer 0.25° ticks
- $\gamma$'s collimated at the source and after LXe scattering
- Coincidence detector: NaI 3" crystal
Data selection

- Selection of full absorption peak (green)
  - asymmetric in energy to reduce multiple scatters
  - asymmetric in ToF to account for early events (few PE pulses in LXe)

- Background estimation from side bands (accidental triggers, blue)
Monte Carlo simulation

• Broad raw energy spectrum
• Asymmetric spectra: $E_{er}$ quadratic in $\theta$ for small $\theta$
• MC data converted into scintillation signal

→ Complete setup simulated with Geant4
  • Multiple scatters: 1.6%
  • Scatters off detector materials: 5.8%
MC/data fitting

- LY is allowed to have a slope in the region fitted
- Systematic uncertainties
  - Scattering angle
  - Variation fit range
  - LY dependence on source strength
  - PMT coincidence requirement
  - LY variations during the measurement
Light yield decreases at 0-field below 40 keV (reduced electron-ion recombination)

Field quenching $\sim 75\%$ at low energies

arXiv:1303.6891
Implications for dark matter search

| Experiment   | $|\vec{E}|$ (V/cm) | $S_{1_{\text{thr}}}$ (PE) | $LY_{\text{Co}}(\frac{PE}{\text{keV}})$ | $E_{\text{thr}}$ (keV) |
|--------------|------------------|---------------------------|---------------------------------------|----------------------|
| ZEPLIN-III   | 3400             | 2.6                       | 1.3                                   | 2.4$^{+0.5}_{-0.4}$   |
| XENON10      | 730              | 4.4                       | 3.0                                   | 1.8$^{+0.4}_{-0.3}$   |
| XENON100     | 530              | 3.0                       | 2.3                                   | 1.7$^{+0.4}_{-0.3}$   |
| XMASS        | 0                | 4.0                       | 14.7                                  | 1.1$^{+0.4}_{-0.2}$   |

→ DAMA signal can be tested in XENON100!

Analysis of time variations of ER rate currently ongoing
Summary

- Scattering of WIMPs off nuclei
  - XENON100 excludes the current indications of DM
  - Energy threshold ($L_{eff}$) verified with MC/data comparison of an AmBe neutron source

- Scattering of light dark matter particles off electrons
  - Compton experiment to determine the energy threshold for electronic recoils
  - XENON100 threshold is at $\sim 2\text{ keV}$
    - sensitive to DAMA annual modulation energy region
  - XENON100 analysis of time variations of the background rate ongoing
Noble gas scintillation process

Nuclear recoil

Excitation: $R^*$

$R^* + R \rightarrow R_2^*$

$R^*_2 \rightarrow 2R + \text{hv}$

Ionization: $R^+$ and $e^-$

$R^+ + R \rightarrow R_2^+$

$R_2^+ + e^- \rightarrow R^{**} + R$

$R^{**} \rightarrow R^* + \text{heat}$

$R^* + R \rightarrow R_2^*$

$R^*_2 \rightarrow 2R + \text{hv}$

singlet

triplet

19 ns

5 ns

3 ns

15 µs

1.6 µs

Neon

Argon

Xenon