Optimization of Non-Gaussian Background Rejection in XENON10
1. Brief overview of XENON10 installation/detector
2. Trigger Threshold / Analysis Threshold
3. Discrimination of ER v NR: Gaussian & non-Gaussian populations
4. Optimization of discrimination
   Gaussian: corrections for detector non-uniformity (optimize sigma)
   Non-Gaussian: identification of anomalous pathologies
5. Discussion of candidate events in XENON10 58.6 Live-Day Result
XENON10 Installation at LNGS

3100 m.w.e. / 20 cm HDPE / 20 cm Pb
XENON10 Detector

15 cm drift (z) defined by SS mesh grids
20 cm Ø defined by Teflon Can
(max 13.5 kg LXe)

89 Hamamatsu R8520-AL PMTs (1” square)
  48 Top Array
  41 Bottom Array

Liquid Xe maintained at
T=180 K and p=2.2 atm.

12 kV cathode
$E_d = 0.73$ kV/cm (drift)
$E_{gas} = \sim 9$ kV/cm (S2)
Direct Detection Event Rate

$\text{m}_{\text{WIMP}} = 100 \text{ GeV}, \sigma_{W-N} = 2.0 \times 10^{-43} \text{ cm}^2$

Integrated Rates Above Threshold

(dash) Rate $\geq E_r$, (line) $dN/dE_r$ [keVr/kg/day]

Recoil Energy, $E_r$ [keVr]

- Green: Xe $A=131$
- Red: Ge $A=73$
- Blue: Ar $A=40$

Differential Rates
Typical Background Event at 4.5 keVee *

**S1**: primary scintillation

**S2**: ionization drifted, extracted, amplified in gas region (secondary scintillation)

**Background Discrimination:**

\[(S2/S1)_{ER} > (S2/S1)_{NR}\]

**x,y coords.**: from S2 Hit-Pattern

**z coord.**: from drift time \(\Delta t\) between S2 and S1

*(scaled using 3.0 phe/keVee from 122 keV gamma cal.)*
Trigger Schemes

S1 Trigger:
1. (1) n-fold coincidence in 80ns window
   (2) 80% single photo-electron acceptance
   (3) 80% light on bottom (trigger) PMTs

S2 Trigger:
2. (1) $\Sigma$(34 top-center PMTs)
   (2) integrate with $\tau = 1 \mu s$
   (3) threshold discriminator

(Final Trigger Solution)

2.3 keVee Background Event

5 phe (!)

3150 phe

Typical PMT spectrum in single p.e. condition:
Gain: $2.20 \times 10^6$
Sigma: $1.13 \times 10^6$

A. Manzur (Yale)

noise peak

single p.e. response
S2 Trigger Threshold: single electron (!)

2.5 Live-Days Background Data (Sept 2006)

- Non-primary / non-Trigger S2
  - $\mu=28$ phe, $\sigma=7.2$
  - S2 which caused a Trigger

**Typical S2 at threshold:**

- ER (2 keVee):
  - 2800 phe ($\sim100$ e-)
- NR (4.5 keVr):
  - 1100 phe ($\sim40$ e-)

**Smallest NR S2 at 4.5 keVr threshold:**

- 300 phe ($\sim12$ e-)

Non-primary S2 => found in event waveform, not necessarily correlated with event energy deposition

Rate $\sim 0.17$ Hz
S1-lookback efficiency \((n \geq 2)\) from MC:

\(~ 99\% \text{ at } 4.5 \text{ keVr}~

Effective S2 analysis threshold \(~300\) phe (12 e-) set by S1 coincidence req. \((n \geq 2)\) and NR \(-3\sigma\) contour

Analysis Threshold >> Trigger Threshold

Monte Carlo Simulation

AmBe Calibration Data
Calibration Data Band Centroid / $-3\sigma$
because ionization yield rises at lower energy

Make a simple coordinate transform (based on $\mu_{ER}$) to remove energy-dependence

DM-Search acceptance box in discrete bins
Discrimination Parameter appears Gaussian

13-17 keVr

NR v ER Band Separation
Improves at low E...

but still need to minimize sigma
to maximize discrimination

50% acceptance for Nuclear Recoils
99.9% discrimination
> 99.5% discrimination

(discrimination calculated from Gaussian fit params.)
Corrections to data improve sigma

±20% variation in S2 across x-y
(±25% in Full Volume)

±10-15% variation in S1 across z
(±28% in Full Volume)

S2 Variation: 40 keV line

Top PMT Array Relative Sensitivity

< 2% variation in S2 with z (electron lifetime > 2ms)

Fiducial Volume

R.S. map obtained by comparing S1 signal in each nearest-neighbor pair, then diagonalizing the matrix
Before Fiducial Volume Cuts

WS 58.6 Live-Day

5649 evts 2–12 keVee
R<9.5cm, 2<z<14 cm
μNR (50% Acc.)

Most (spurious) events in box are removed by Fiducial Volume Cuts

DRU = 1 cts/keVee/kg/day

Electric Field Simulation

Mass of fiducial volume: [kg]
2.3, 3.6, 6.4, 7.5, 10.2, 13.5

Event Rate (DRU)

R. Gomez (Rice)
L. deViveiros (Brown)
After Fiducial Volume Cuts

still have 23 events (a significant fraction appear non-Gaussian).

13 events (+) removed by (primary analysis) cut targeted at anomalous S1 hit-pattern

origin of non-Gaussian tails in ER distribution: 
**Gamma X events**
Gamma X: what is it? 

Example:
if the 2nd scatter happened below the cathode grid, its S2 would be absent.

Result:
S2/S1 decreases, which can make an electron recoil look like a nuclear recoil.
How to spot a Gamma X Event: S1 Hit-Pattern

Scatter in center of FV

Scatter close to bottom of FV

Gamma X scatter

Events in Fiducial Volume => diffuse Hit Pattern

Events near bottom => more localized Hit Pattern

Events below cathode => highly localized Hit in ~ 1,2 PMTs

Primary Analysis Gamma X cut:

\[ S1_{RMS} = \sqrt{\frac{1}{n} \sum (S1_i - \bar{S1})^2} \]
Events remaining in box are NOT dark matter... they are **Gamma X** events

XENON10 58.6 Live-Day Result

10 Events in box  (Yellin Maximal Gap, no BG subtraction, 50% NR acceptance, 86% cut acceptance)

SI Cross-Section Exclusion Limit
136 kg-days
A More Sophisticated Gamma X Cut

$phe/PMT$

5

2

1

0.5

0

$S_{1_{\text{max bottom}}} / \sum S_{1_{\text{bottom}}} \times \sqrt{S_{1}}$

$S_{1}$ Hit Pattern

$S_{1} = 18 phe$

also for 2, 3, 4 PMT (w localization req.)

Monte Carlo Simulation

Cuts developed as part of an independent (secondary) blind analysis

Peter Sorensen

DSU 2007

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Identifying Anomalous Topologies

Subset of Gamma X events with signal concentrated in 2 PMTs: Resistor-Chain Events

Rare Effect: ~ 10 events in combined WS background data + Cs calibration data (175 Live-Days Equivalent)

Resistor-Chain (for drift E-Field) Pocket is filled with LXe

Peter Sorensen
DSU 2007
Edge Gamma X Events

Subset of Gamma X events with signal concentrated in **Edge** PMTs

\[ \frac{\Sigma S_{\text{edge}}}{\Sigma S_{\text{all}}} \]

could indicate a 2nd scatter near edge of the detector, where there are regions of reduced/zero drift field

Monte Carlo Simulation

- 96.7%
- 96.5%
- 97.7%
- 97.9%
- 96.7%
- 98.9%

\[ 1^{37}\text{Ca Cal. Data} \]
\[ \text{Cut Band} \]
\[ y < \text{ER 99.9\%} \]
Gamma-X Monte Carlo

- We have simulated the expected Gamma-X background due to gammas generated in the detector (i.e. PMT radioactivity).

- We have found the rate for Reverse Field Region Gamma-X events to be subdominant for our ER vs NR discrimination – their rate at low energies (<25keV) is 1mdru or less.

- Comparing the spatial distribution of events
  - $10^{-3}$ DRU x 10keVee x 5.3kg x 59livedays = ~3 events
Cut Efficiencies for AmBe NR Calibration Data

Efficiency shown for secondary analysis (primary analysis is within 1%)
10 Events in box:
5 are consistent w Gaussian ER background
5 are NOT.

Events 1, 6, 8, 10 removed by Secondary (blind) Cuts:
- #6: Gamma X (Resistor-Chain Hit-Pattern)
- #8: Gamma X (Resistor-Chain Hit-Pattern)
- #10: Gamma X (Anomalous Edge Hit-Pattern)
- #1: Coincidence n=1 (Requirement: n=2)

Event 2 almost removed by Secondary (blind) Cuts:
Gamma X (signal concentrated in 3 PMTs)
a posteriori 1% decrease in acceptance => would have been cut

Discrimination challenges we can certainly overcome:
Maximize discrimination against Gaussian leakage by correcting for instrumental (detector) variation (x,y,z position / PMT)
Non-Gaussian Pathologies seem to arise predominantly from “dead” regions of LXe

Summary
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