Light from Light Dark Matter and XENON100

For the XENON100 Collaboration
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The XENON Collaboration

~60 scientists from 12 institutions:
- University of California Los Angeles
- Rice University Houston
- Columbia University New York
- Universidade de Coimbra
- Subatech Nantes
- NIKHEF Amsterdam
- Willhelms Universität Münster
- Max-Planck-Institut Heidelberg
- Universität Zürich
- Laboratori Nazionali del Gran Sasso
- INFN e Università di Bologna
- Jiao Tong University Shanghai
Particle Detection Channels

Scintillation
- ZEPLIN-I, KIMS, DAMA, LIBRA

Ionization
- CoGeNT, GENIUS-TF, HDMS, XENON100?

WIMP
- XENON10/100/1t, ZEPLIN-II/III, LUX, WARP

Phonons
- CRESST-I, CUORICINO

Target

COUPP

Bubble Nucleation
- CDMS, EDELWEISS
Dual-Phase Xenon TPC

3D position information
S2 hit pattern: $\Delta r < 3\,\text{mm}$
Drift time: $\Delta z < 2\,\text{mm}$

gas xenon
liquid xenon

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Recoil Discrimination > 99%

$e^-/\gamma$: electron recoil

$n$/WIMPs: nuclear recoil

$\frac{S_2}{S_1}$, $n, \chi \ll \frac{S_2}{S_1}$, $e, \gamma$

→ lots of information for each event
Recoil Discrimination > 99%

\( e^-/\gamma \): electron recoil

\( n/WIMPs \): nuclear recoil

10keV\(_{nr} \) WIMP yields

- \( \sim 160 \) S1 photons, detect \( \sim 10 \)
- \( \sim 70 \) S2 electrons, generate \( \sim 10^4 \) photons, detect \( \sim 1750 \)
XENON100

98 PMT
top array

80 PMT
bottom array
XENON100

- veto PMT
- bell
- 98 PMT
- top array
- PTFE TPC, field shaping
- 80 PMT
- bottom array
- veto PMT
- 160kg liquid xenon
- +4500V
- -16000V

Matter and XENON100
PMTs & Gain Calibration

- 1” square metal-channel R8520-06-Al
- optimized for 178nm, low T, high p
- low radioactivity <1mBq in $^{238}\text{U}/^{232}\text{Th}$ per PMT
- 98 top PMTs, optimized for good r resolution
- 80 bottom PMTs, optimized for filling factor, QE ~33%
- 64 in veto looking up, down and inward
- regular gain monitoring
Design for Electric Field

- hexagonal electrode meshes
- cathode at -16kV
drift field 0.53kV/cm
- anode at 4.5kV
extraction field 6kV/cm (LXe)
12kV/cm (GXe)
- 40 doubled field shaping rings
DAQ

- 242 PMTs
- 400μs waveform
- 100MS/s, 14bit flash ADC
- zero-length-encoding (on-board FPGA)
- dead-time free during background data taking

(1km of cables inside the detector, 3km outside)
XENON100 Shield

20cm $\text{H}_2\text{O}$, 15cm Pb, 5cm French Pb, 20cm PE, 5cm Cu
Screening & Simulation

dedicated HPGe setup @ LNGS

Simulation agrees with data
Spatial Distribution

Gammas: main contribution from PMTs highly localized

Neutrons:
• $^{81}$Kr: 281keV electron capture, long decay, abundance $^{81}$Kr/Kr $\sim 10^{-13}$ → irrelevant

• but $^{85}$Kr beta decays (687keV), natural abundance $^{85}$Kr/Kr $\sim 10^{-11}$
• use dedicated distillation column to get Kr to $\sim 100$ppt level
How to Ensure Kr at That Level?

$^{85}\text{Kr}$

- $Q_\beta = 687$ keV
- 99.6% $^{85}\text{Rb}$
- 0.4% $^{85}\text{Kr}$
- 10.8y
- 1.0 $\mu$s
- 514 keV

$^{85}\text{Rb}$

- stable

- use delayed $\beta-\gamma$-coincidence to tag events in situ
- only 0.4% branching

XENON100:
- tagged 6 events in 60.6 live days
- $\geq 143^{+140}_{-81}$ ppt

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Example with Full 30cm Drift

electron lifetime during background data taking 154μs to 192μs

S1: 498pe
S2: 41609pe

drift 174μs

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Position Reconstruction

test with collimator: resolution < 3mm (~anode mesh pitch)
Position Dependent Corrections

S1 light collection

S2 electron lifetime

S2 x-y-dependence
Calibration with $^{83}\text{mKr}$

$^{83}\text{Rb}$

$Q_{EC} = 910$ keV

$86$ d, $92\%$

$32$ keV, $1.842$ h

$9$ keV, $147$ ns, stable

$^{83}\text{Kr}$

Pulse height / nV

$30$ keV $S_1$, $9$ keV $S_1$, $30$ keV $S_2$, $9$ keV $S_2$

Time / channels (10 ns)

decay

drift
Position Dependent Corrections

$^{137}\text{Cs}$ taken with low anode
S1 r-z-Correction
S2 x-y-z-Correction
Inelastic Scatters & Fiducialization

Electronic recoils during $^{241}$AmBe calibration:

- $^{129}$Xe (40 keV)
- $^{131}$Xe (80 keV)
- $^{19}$F (110 keV)
- $^{131m}$Xe (164 keV)
- $^{19}$F (197 keV)
- $^{129m}$Xe (236 keV)

Full volume 30 kg fiducial
Single Electrons

typical waveform:
Single Electrons

time correlation:

typical waveform:

time constant $\approx 135 \mu s$
Single Electrons

position correlation:

typical waveform:

time constant $\approx 135 \, \mu s$
Single Electrons

low S2 spectrum:

typical waveform:

time constant $\approx 135 \mu s$
Nuclear Recoil Equivalent Energy

Nuclear Recoil Energy: 

\[ E_{nr} = \frac{S1}{L_y} \cdot \frac{S_{ee}}{S_{nr}} \cdot \frac{1}{\mathcal{L}_{eff}} \]

\[ L_y(122\text{keV}_{ee}) = (2.20 \ 0.09)\text{PE} \]

\[ S_{ee} = 0.58 \]

\[ S_{nr} = 0.95 \]
Nuclear Recoil Equivalent Energy

Nuclear Recoil Energy: $E_{nr} = \frac{S1}{L_y} \cdot \frac{S_{ee}}{S_{nr}} \cdot \frac{1}{\mathcal{L}_{eff}}$

$L_y(122\text{keV}_{ee}) = (2.20\ 0.09)\text{PE}$

$S_{ee} = 0.58$

$S_{nr} = 0.95$

$\mathcal{L}_{eff}$ best fit

Manzur et al. 2010
Aprile et al. 2009
Chepel et al. 2006
Aprile et al. 2005
Akimov et al. 2002
Bernabei et al. 2001
Arneodo et al. 2000
formally a non-blind analysis since data was open, in reality analysis developed on calibration data only
Quality Cuts from Calibration

- reject PMT single PE: require one two-fold coincident S1 pulse in the waveform
- reject double scatters: require one S2>300PE and no signal in veto during 20ns around the S1 pulse
- reject electronic artifacts: no obvious noise
- reject events not from fiducial volume: S2 width consistent with drift time
Neutrons from $^{241}$AmBe

energy range 7.4-29.1 keV$_r$
(4-20 PE, S1 coincidence with >90% efficiency above 4PE) and below nuclear recoil median
Electron Recoil Band

Compton scatters from $^{60}$Co

50% nuclear recoil acceptance gives >99% discrimination at low energies
Cut Acceptance

consider every event cut by only one cut as valid event

expect improvements of cuts in the future
Discrimination

11.17 days, 40kg fiducial, 30%-40% efficiency

no events close to or below the nuclear recoil median
even below 4PE
Discrimination

11.17 days, 40kg fiducial:

(no events even at 84% acceptance)
Fiducialization

11.17 days, 40kg fiducial, 30%-40% efficiency

no nuclear recoils anywhere near the fiducial volume
characteristic velocity 220km/s, Earth velocity 232km/s, escape velocity 544km/s, local density 0.3GeV/cm², Helm Formfactor, Poisson dominated energy resolution
Resulting Limit

excludes CoGeNT and DAMA favored regions at 90% c.l.
robust: fiducial volume, discrimination, cut acceptance, energy threshold all very conservative!

on the arXiv tomorrow