Neutrino-induced recoils in liquid xenon TPCs

v-e Scattering at Low Energies
ACFI, UMass Amherst
April 2019

Evan Shockley
Kavli Institute for Cosmological Physics
& University of Chicago
Low-threshold, low-background detectors that are scalable

- Noble liquids, w/ focus on xenon here

Scintillation (S1) and ionization (S2) signals allow for:

- 3D position reconstruction
- Energy reconstruction
- Particle identification
  - Electron recoil (ER) from $\gamma$, $\beta$, $\nu$
  - Nuclear recoil (NR) from neutron, $\nu$, WIMP?

Experiments
XENON program, LUX, LZ, Panda-X, DarkSide
Two analysis thresholds

1. S1 + S2

- ~1 keV energy threshold
  - driven by light yield & S1 coincidence requirement (3 PMTs most likely)

- Stronger position reconstruction

- Stronger background modeling & rejection

- ‘discovery’ analyses

2. S2-only

- O(100) eV energy threshold

- Complete background model difficult —> typically ‘limit-only’ analyses

See Graham’s talk (next)
Two analysis thresholds

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See Graham’s talk (next)

Focus mainly on S1 + S2
...low background...

- Shielding: underground + muon veto
- $\gamma$-ray from materials reduced via screening + fiducialization
- "Intrinsic" sources: 222Rn, 85Kr, 136Xe
  - more details later
- $v$-$e$ elastic scattering

- Neutrons
- Coherent elastic $v$-nucleus scattering (CEvNS)
ER/NR discrimination

- ER vs NR discrimination > 99%
  - NRs display less ionization (S2) for given scintillation (S1) due to more electron-ion recombination
- That < 1% ER leakage still dominant background — suppressing ER is critical!

NR signals ‘quenched’ due to energy loss to heat — different energy scales

Evan Shockley (KICP/Chicago). v-e Scattering Workshop. UMass, April 2019

NEST model

arXiv 1307.6601
...that are scalable

Fiducial mass

ER background level

XENON10
0.005 ton

XENON100, LUX, PandaX
0.06-0.3 ton

XENON1T
1.3 ton

today

XENONnT, LZ
5-6 ton

DARWIN
30 ton
XENON1T WIMP analysis

- Search for NR above background
- Profile-likelihood analysis in (at least) S1 + S2 space
- ~800 total events in 1 ton*year exposure

Beyond the WIMP search: ER signals
Combined Energy Scale

\[ E = W(n_{ph} + n_e) \]

\[ \frac{E}{W} = \frac{S_1}{g_1} + \frac{S_2}{g_2} \]

\[ S_2 = -\frac{g_2}{g_1} S_1 + \frac{g_2}{W} \]

\[ Q = -\frac{g_2}{g_1} L + \frac{g_2}{W} \]

\[ W = 13.7 \text{ eV} \]

- Use anti-linearity of S1 & S2 to define ‘combined energy scale’ (CES)
- Easy to model — no need to worry about energy dependence of photon/charge yields
- With knowledge of g1 & g2, easy to reconstruct energy from S1, S2

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**ER Backgrounds: Kr85**

- **β-emitting noble gas, distributed uniformly in xenon liquid/gas**
  - not removed by fiducialization cuts, *in situ* purification (getters)

- Removed via cryogenic distillation (XENON1T/nT) or gas charcoal chromatography (LUX/LZ)
  - 100 ppb to 0.66 ppt in XENON1T
  - Level of 0.026 ppt already reached in the lab
  - goal of ~0.01 ppt in XENONnT/LZ/DARWIN

ER Backgrounds: Rn222

- β-decay of Pb214 - distributed uniformly in liquid/gaseous xenon
- Online Rn distillation column in future detectors
  - Test with XENON1T saw ~20% decrease in Rn
- Goal: 1 μBq/kg Rn concentration (factor of 10 improvement)

XENON1T Rn Budget

- Cryopipe: 26%
- Getters: 31%
- TPC + cryostat: 19%
- Piping + Cables: 20%
- QDrive Pumps: 4%

XENON1T Rn Budget

- Goal: 1 μBq/kg Rn concentration (factor of 10 improvement)
ER Backgrounds: Xe136

- 2νββ decay with $T_{1/2} \sim 10^{21}$ year
- 8.8% natural abundance
  - Could be removed by isotopic depletion?

ER Backgrounds: Xe124 (!!!)

- 2νECEC decay with $T_{1/2} \sim 10^{22}$ years, the longest half-life measured to date
- Peak at 64.3 keV, so not too relevant for $\nu$ searches

Nature 568 7753 (2019)
Progress/projections of total ER background (low energy)
ER **Signals:** solar neutrinos

- Precision measurement of the dominant pp $\nu$ flux
  - Constrain stellar physics such as energy production
  - $\nu$ oscillations at low energy
- CNO measurements possible in Darwin?
  - See Newstead, Strigari, Lang (2018); and Louis’ talk from Thurs.
- Physics beyond SM?

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JCAP 1611 (2016) no.11, 017

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**Borexino:** Nature **562**, 505–510 (2018)

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Evan Shockley (KICP/Chicago). $\nu$-e Scattering Workshop. UMass, April 2019
Solar ν toy models

<table>
<thead>
<tr>
<th></th>
<th>Kr85 (ppt)</th>
<th>Rn222 (μBq/kg)</th>
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<tr>
<td>XENON1T</td>
<td>0.66</td>
<td>10</td>
<td>no</td>
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<tr>
<td>LZ/XENONnT</td>
<td>0.015/0.01</td>
<td>2/1</td>
<td>no</td>
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<td>DARWIN</td>
<td>0.01</td>
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Dominated by solar ν!
Neutrino Magnetic Moment

\[ \frac{d\sigma}{dT} \sim \mu^2 \left( \frac{1}{T} - \frac{1}{E_\nu} \right) \]

- Rough sensitivity estimates using low-energy ER framework of XENON1T
  - assumes XENON1T efficiency and resolution
  - FEA assumed (See Chih-Pan’s talk Friday)

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<td>5.6</td>
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<td>0.015</td>
<td>2</td>
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<tr>
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<tr>
<td>LZ/nT</td>
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<tr>
<td>DARWIN</td>
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**Maybe fudge factor of ~2?**

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Caveats

You’re the first people I’ve shown this to

- Here’s the model at sensitivity value — seems a bit optimistic.
- Systematic uncertainties such as efficiency ignored
- Nuclear recoils ignored

Rough sensitivity estimates using low-energy ER framework of XENON1T - assumes XENON1T efficiency and resolution - FEA assumed (See Chih-Pan’s talk Friday) Likely world-leading sensitivity!
Supernova Neutrinos

- XENON1T + future TPCs subscribe to SNEWS (“supernova trigger”)
- Look for CEvNS from SN neutrinos
  - flavor-independent
  - requires S2-only analysis, but..
  - Timing information allows for discovery analysis

Lang et. al. arXiv 1606.09243

S1 falls mostly below threshold
Other signals?

- Neutrino millicharge
- Charge radius
- Dark photon + (heavy) sterile neutrino
- What’s interesting? Please advise.

Harnik, Kopp, Machado (2012)
A bit more on S2-only

✦ S2-only is difficult, but we’re not ignoring it
✦ LBECA group working on small LXe TPC focused on single electron studies
  - couldn’t find a paper, but here are some slides from P. Sorensen via google: http://online.itp.ucsb.edu/online/hepfront-c18/sorensen/pdf/Sorensen_HEPFront18Conf_KITP.pdf
✦ Backgrounds (that we ~ know of)
  - Photoionization
  - Delayed extraction?
  - Impurities!
  - Grids, rings etc.
✦ Work ongoing to suppress/understand backgrounds
Summary

- Liquid xenon TPCs are low-threshold, low-background detectors that are scalable
  - Sensitive to much more than just WIMPs!

- Dominant ER backgrounds will continue to be suppressed in future TPCs, eventually being dominated by solar neutrinos

- XENON1T could set world-leading constraints on neutrino magnetic moment right now
  - LZ/nT gain additional order of magnitude with long exposure

- Future xenon TPCs such may probe $\mu_{\text{eff}} < 1 \times 10^{-12} \mu_B$ with optimistic (but not unrealistic) assumptions

Thank You.
Backup
Dark absorption & solar axions

- Dark absorption of axion-like particles (ALPs) or dark photons
- Non-relativistic: mono-energetic electron recoil

QCD axions produced in the sun
- not dark matter
Absorbed via axio-electric effect
For Type-I Sources the Rn-concentration in the active volume depends only on circulation rate. Distill the xenon fast enough wrt $^{222}\text{Rn}$ mean lifetime (5.5 days).

• High-flux online cryogenic distillation column:
  ➡ Same concept as other tested columns, just more powerful (~3kW)
  ➡ Extracting xenon from active volume @ 200slpm (8t in ~ 5d);
  ➡ Intrinsic reduction factor ~100;
  ➡ Overall reduction in the active volume ~2;
  ➡ Designed to be upgradable to ~600slpm

Slide credit: L. Grandi
Radon reduction Strategy

- A single dedicated column to remove Rn emanated in *gaseous* and *liquid phase*.

- **Under assembly** @ MÜNSTER

- *Integrated* within existing *liquid* and *gaseous recirculation system*.

- **Radon-screening facility** @ MPIK working at full load to certify material and cleaning procedures, to further reduce Rn-sources wrt to XENON1T.
NEW dedicated cryogenic distillation column:

- operated continuously to extract xenon gas (from pipes, etc, …) and remove $^{222}$Rn emanated by Type-II sources:
  - extraction flow of xenon gas $\sim 20$ slpm;
  - reduction factor $\sim 100$.

The concept was:

- **Successfully tested** in XENON100 [EPJ C 77 (2017) 358]
- **Successfully tested** in XENON1T
  - operated Kr-column in reverse mode to mimic a Rn-column (@ 3 slpm, non-optimized).
  - Measured 20% reduction of the background (despite not being optimized).