The Noble Element Simulation Technique v2.0.1

Greg Rischbieter
University at Albany -- PhD Candidate
April APS 2020
On Behalf of the NEST Collaboration
About NEST

● “Inter-collaboration” Collaboration
  ○ Members from LUX/LZ, XENON, DUNE, nEXO, RED100, and COHERENT

● Fast, stand-alone C++ code with robust example executable: testNEST
  ○ Python version “nestpy” available too!
  ○ Reproduces LXe scintillation and ionization response from most imaginable interaction types
  ○ Yields as a function of particle type, energy, field, density and target phase
  ○ Temperature, pressure, and density dependencies from NIST
  ○ Xenon only? Not for long! LAr models imminent! (See J. Mueller’s talk in session X14)

● GEANT4 Integration
  ○ Takes energy depositions and returns light and charge yields

● nest.physics.ucdavis.edu & github.com/NESTCollaboration
  ○ Useful tools on the website! Interactive Yields Calculator; plots of all NEST models
Gaining Momentum

- Since its release in 2018, the NESTv2 code has been cited at least 14 times in the literature according to Zenodo
  - Cited multiple times by large collaborations like XENON, LUX/LZ, and nEXO
  - Various other citations from smaller groups and independent studies
  - (Plenty more known citations not yet identified by Zenodo)
  - NEST publications have over 300 citations in total

NEST is growing and becoming more widely-recognized in our community!

As more groups use NEST, it will be easier to compare results as we strive for a “community standard” for yield comparisons

So if you’re not using NEST, you should!
The Whole Point:
Providing a Data-Driven Mapping from Observables to Fundamentals

Signal production in xenon

\[ \text{Xe}^+ + e^- \xrightarrow{\text{Escape}} \text{Ionization (S2)} \]

\[ \text{Xe}_2^* \xrightarrow{\text{Recombination}} \]

\[ \text{Xe}_2^* \xrightarrow{\text{De-excitation}} \text{Scintillation (S1)} \]

\[ \text{Xe}_2^* \xrightarrow{\text{Biexcitonic quenching}} \text{Heat (not detected)} \]

NEST: What to Expect (from calibrations/backgrounds)

NEST: Explain what was Observed (Modeling Detector)
Nuclear Recoils
Recently Updated in NESTv2.0.1 !!

![Graph of Nq vs. Energy](image)

\[ N_q = \frac{\mathcal{L} \cdot E}{W} = \alpha E^\beta \]

- **Procedure:**
  - Collect world data; correct for newly understood phenomena; fit functions of field and energy to reproduce data
- **Light Yields (photons/keV) shown, similar treatment for Charge Yields**
- **Detailed report available on NEST Website**

\[ N_{e^-} = \frac{E}{TIB(\rho, \varepsilon) \cdot \sqrt{E + \varepsilon}} \cdot \left(1 - \frac{1}{1 + \left(\frac{E}{\varepsilon}\right)^{\eta}}\right) \]

\[ N_\gamma = (N_q - N_{e^-}) \cdot \left(1 - \frac{1}{1 + \left(\frac{E}{\zeta}\right)^{\varepsilon}}\right) \]

**β Electronic Recoils**

- **Constant Total Quanta:** $N_{e^-} + N_{\gamma} = \frac{E}{W}$
- **Same Procedure as NR, with anti-correlated light and charge yields**
- **Charge Yields** (electrons/keV) shown
- **Also a good approximation of Compton Scatter data**
  - $^{137}$Cs Compton Scatters included in fit
- **Covers out to MeV range for $0\nu\beta\beta$ decay searches**

$$N_{e^-} / E = m_1 + \frac{m_2 - m_1}{(1 + m_3 E^4)^{m_5}} + \frac{m_6}{(1 + m_7 E^{m_8})}$$
Pulse Shapes

- Uses event position and detector geometry to approximate photon travel time.
- Matches LUX pulse shape discrimination.
- Simulates both components of SE noise in LXe (fast and slow components).

Two distinct components of the delayed single electron noise in liquid xenon emission detectors
P. Sorensen (LBNL, Berkeley), K. Kamdin (LBNL, Berkeley & UC, Berkeley). Nov 19, 2017. 5 pp. Published in JINST 13 (2018) no.02, P02032

Liquid xenon scintillation measurements and pulse shape discrimination in the LUX dark matter detector
Accurately reproduces both 32.1 keV and 9.4 decays, as well as merged 41.5 keV

Robust time-dependent model

Matches individual decays as well as ‘merged’ decay

---NEST: 9.4 keV
---NEST: 32.1 keV
---NEST: 41.5 keV
Again, only worked by correcting data for extraction efficiency, as on slide 5 (NR).

- Good agreement for strong fields for a full range of relevant energies

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Simultaneous measurement of ionization and scintillation from nuclear recoils in liquid xenon as target for a dark matter experiment


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Preliminary Error Bands!
Complete with Detector Modeling

Calculates fluctuations about the mean yields (statistical and recombination fluctuations!)

Accurately simulates and reproduces ER “leakage” into NR band

Can add in custom detector files to simulate your own detector
Conclusion

- NESTv2 is a powerful simulation tool free to use, and it takes seconds to run!
  - Constantly improving with new public data → **v2.1.0 expected soon**!
- Accurately simulates many different interactions in LXe and GXe, while Argon models are being worked on as we speak.
  - User-friendly code so you can add any other interactions that you might find useful.
  - Both C++ and python versions available
- You can build your own custom detector file and create signal and background models and reproduce calibrations
  - LUX Run3 (WS2013) used as the default detector, and XENON10 included too!
- Get yourself a copy!
  - [https://github.com/NESTCollaboration/nest](https://github.com/NESTCollaboration/nest)
  - [nest.physics.ucdavis.edu](nest.physics.ucdavis.edu)
Thank You!
Backup Slides
Not a fan of C++? No Problem!

Thanks to pybind11, you can happily enjoy all of NEST’s offerings in your favorite python environment

nestpy

These are the Python bindings for the NEST library, which provides a direct wrapping of functionality. The library is not Pythonic at this point but just uses the existing naming conventions from the C++ library.

You do not have to have NEST already installed to use this package.

Installing from PyPI

For 64-bit Linux or Mac systems, install `nestpy` should just require running:

```
pip install nestpy
```
Previous Yield Models: Thomas-Imel vs. Doke-Birks

- In terms of recombination: \( QY = n_{e^-} / E = \frac{(1-r)}{E} \cdot N_{ions} \)
  - \( N_{ions} \) is approximately energy divided by the work function: \( E/W \)

- Thomas-Imel Box Model → Low energy approximation (no particle track)
  - Quanta are spherically distributed
  - \((1-r) = \frac{1}{\xi} \ln(1+\xi)\) where \(\xi \equiv A \cdot N_{ions}\) for some constant, \(A\)
  - So \( QY = \frac{1}{A \cdot E} \cdot \ln(1 + A \cdot \frac{E}{W}) \)
  - At 180 V/cm, \(A = 0.03\) and expanding about \(E=2\) keV, \(QY \approx 25.6 - 6.85\Delta E + 2.18\Delta E^2 + O(\Delta E^3)\)
    - NEST Model at 180V/cm about 2 keV: \(QY \approx 34.67 - 12.67\Delta E + 4.7\Delta E^2 + O(\Delta E^3)\)

- Doke-Birks → High energy approximation (particle create tracks)
  - Quanta are cylindrically distributed (superposition of many spheres)
  - \( QY = \frac{N_{ions} / E}{1 + k_B \cdot dE/dx} \), and \(dE/dx \sim E^{-3/4}\) for xenon at keV-range energies (\(k_B\) is Birk’s constant)
  - So now, \( QY = \frac{1}{1 + k_B^* \cdot E^{-3/4}} \) (11)
  - At 180 V/cm, \(k_B^* \approx 42\) and expanding about \(E=100\) keV, \(QY \approx 26.6 + 0.11\Delta E - 0.0005\Delta E^2 + O(\Delta E^3)\)
    - NEST Model at 180V/cm about 100 keV: \(QY \approx 26.7 + 0.12\Delta E - 0.0005\Delta E^2 + O(\Delta E^3)\)
NR Charge Yields
Fit to World Data

Scintillation Signal v. Time

Kr83m data suggests that the total light yield from the 9.4 keV decay has a slight time dependence.

Response of liquid xenon to Compton electrons down to 1.5 keV
Published in Phys.Rev. D87 (2013) no.11, 115015
\(\alpha\)-Model for GXe

- Most GXe \(\alpha\) data is contradictory (data shown is 0 V/cm).
- NESTv2 splits many of the differences between contradictions.
  - Floating “zero-field” was critical here!

Ionization and scintillation of nuclear recoils in gaseous xenon

Absolute primary scintillation yield of gaseous xenon under low drift electric fields for 5.9 keV X-rays

doi: 10.1109/23.106674

*Light yields (1000 / W) were nearly constant for field ranges ~200-25000 V/cm

[1] states $W_i = 24.7$ eV -- NEST result is 30.2 eV

** Gamma Model found 83.8 eV for 662 keVee
ER from γ-rays

- γ ER different from β ER

Error Bands are PRELIMINARY!
The new EXO yields calibration includes a measurement of the average work function (W) 

Disagrees with accepted results by ~15% 

Existing measurements of W agree with 13.7 +/-~0.2 eV
**W-value: Excess light yield?**

Points include CS and photoabsorption, so expect to fall between beta and gamma.

Qy seems ~correct, while Ly is high
- Additional IR photons detected by APDs?
- Add 35% to Ly for silicon PDs
- Adding ~15% to both Ly & Qy doesn’t work

(Green is modified NEST model)

Least kludgy method - assumes everyone is right

IR scintillation is expected (but not this much)

Need more measurements

- Want to verify our explanation
- If confirmed, IR scintillation will need to be measured and modeled. A structured 35% effect might change the field/energy dependence, or even break the combined energy model (no more 1:1 recombination?)