Noble Element Simulation Technique
Version 2.0

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on behalf of the NEST collaboration
About NEST

- NEST (Noble Element Simulation Technique) is an unprecedentedly accurate and comprehensive simulation of the scintillation, ionization, and electroluminescence processes in noble elements.
- Applications:
  - Direct dark matter searches (LUX, LZ, XENON10, PandaX...)
  - Double beta decay searches (ever in a low energy ranges (nEXO, etc.)
  - Much more!
### What’s New?

<table>
<thead>
<tr>
<th>NESTv1.0</th>
<th>NESTv2.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Only GEANT version</td>
<td>Standalone &amp; GEANT versions</td>
</tr>
<tr>
<td>No alphas and heavy ions</td>
<td>Alphas and heavy ions simulations included</td>
</tr>
<tr>
<td>All equations based on theoretical models</td>
<td>Using sigmoids (family of S-shape functions), which still closely resemble those models.</td>
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<tr>
<td>(Thomas-Imel box, Doke-Briks, etc.)</td>
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</table>
What’s New?

- Revisited old data, corrected for newer phenomena
  - Includes 2PE effect for VUV photons in PMTs
  - Allowed ‘zero-field’ to vary (i.e. took into account possible errors in detectors’ electronics)
  - Allowed extraction efficiency to vary
  - ER: $\beta$-model vs. $\gamma$-model
- Exciton-Ion ratio is energy-dependent
- Accurately models detector effects for S1-S2 bands (means, widths, leakages)
Nuclear Recoils

- Total quanta (light+charge) is now a power law
  - $12.6 \times (\text{Energy})^{1.05}$
    - Elegant $\rightarrow$ almost linear
  - $12.6 \pm 0.9$ & $1.05 \pm 0.05$

- Mean-yields equations replaced with simple functions

\[
\text{Qy} = \frac{1}{A \times (\text{energy} + B)^{0.5}}
\]
Nuclear Recoils

Agrees with known data in 1-sigma margin of error, including high fields experiments.
Electronic Recoils -- Sum of Two Sigmoids

- Smooth transition between low and high energies
- \( Ly + Qy = \text{const} \)

Beta electron recoils: Ly and Qy
Electronic Recoils

Two separate models for ER: beta and gamma
Pulse shapes and single electrons

- Matches LUX pulse shape discrimination
- Can also simulate single electrons!
- Simulates SE noise in LXe

Histograms of scintillation photons arrival times

Dashed lines are NESTv2

Single photo-electrons

Single electron
83mKr

- Robust time-dependent model
- Matches individual decays as well as ‘merged’ decay

\[ ^{83}\text{Kr}^m \]

\[ ^{83}\text{Kr}^m 1/2^- \quad 32.1 \quad 9.4 \quad 0 \quad \text{stable} \]

\[ ^{83}\text{Kr} \quad 9/2^+ \quad 41.5 \quad 1.83 \text{ hours} \]

---NEST: 9.4 keV
---NEST: 32.1 keV
---NEST: 41.5 keV
- 1σ agreement with LUX and XENON100

<table>
<thead>
<tr>
<th>Drift Field (V/cm)</th>
<th>Photons/keV, Electrons/keV</th>
<th>NEST Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>LUX Ly</td>
<td>180</td>
<td>53.4 ± 1.4</td>
</tr>
<tr>
<td>LUX Qy</td>
<td>180</td>
<td>19.4 ± 1.4</td>
</tr>
<tr>
<td>XENON100 Ly</td>
<td>366</td>
<td>52.5 ± 1.8</td>
</tr>
</tbody>
</table>
α-Model

- L-factor fixed by fitting to Adam Bradley’s thesis data
  - (LUX: 180V/cm)
- Still uses Thomas-Imel box model here
  - Energy-independent for simplicity
α-Model

- Worked by slightly correcting data for extraction efficiency
- Good agreement for strong fields
Drift velocity

- NEST also simulates drift velocity for various xenon temperatures and states
- Has good agreement with old and new data
Energy Resolution

- **Quantum Fluctuations**
  - First estimates of fluctuations in energy resolution and fluctuations in quanta produced were by Ugo Fano in the 1940’s.
  - There is energy “lost” when photons are produced in LXe from electron recoils!
  - \( E = W*(n_\gamma + n_e) \rightarrow \) Work Function: \( W = 13.7 \text{ eV} \)
  - Fluctuations modeled using an empirical “Fano-like” factor proportional to \( \sqrt{\text{energy}} \times \sqrt{\text{field}} \)

- **Recombination Fluctuations**
  - Binomial recombination has never matched data well.
  - Same equation as cited in LUX Signal Yields Publication: \( \sigma_T^2 = (1-p)*n_i*p + (\sigma_p n_i)^2 \)
    - \( \sigma_p \) in NEST is both field-dependent and energy-dependent
Recombination Fluctuations

- Comparing to Eric Dahl’s PhD thesis data.
- Corrected Dahl data for overestimation: corrected 15% downward for 2PE effect and extraction eff.

\[ \sigma_T^2 = (1-p)*n_i*p + (\sigma_p n_i)^2 \]
Good fit to LUX Run 3

$\beta$-model better at lower energies. Fit here uses a weighted combination of NEST’s $\beta$ and $\gamma$ models
Energy Resolution: ZEPLIN-III

NEST matched original Z-III resolution (99.999% on AmBe and beta data) and AmBe and beta distributions (ever means)

Light blue → NESTAmBe data
Green → NEST β data
Energy Resolution: XENON10

- Good agreement with XENON10 energy resolution
  - Optimized a Fano-like factor for best agreement → Data suggested field & energy dependence
  - Data suggests that the Fano factor is both energy-dependent and field-dependent
- Magenta stars are $^{129m}\text{Xe}$ & $^{131m}\text{Xe}$
  - Decay in many steps, used NEST to combine the yields from each decay and added them together
  - $^{83m}\text{Kr}$ model suggests that multi-step decays have subtle time-dependence
Argon NEST

• Argon NEST is under-development version of NEST for argon
• Assumption: both Xe and Ar are noble elements – and formulae would be similar sigmoid functions for Ar too
• Empirical models for argon are very important – because theoretical models sometimes are contradictory to each other
• Preliminary models for NR and ER are ready
• Kr and heavy ions models are under development
Conclusion

- NESTv2 is a powerful simulation tool, which now has two versions: standalone tool and GEANT4 library.
- Accurately simulates many different interactions in LXe and GXe (argon models currently in process)
- User-friendly code so you can add any other interactions that you might find useful.
- Get yourself a copy!
  - [https://github.com/NESTCollaboration/nest](https://github.com/NESTCollaboration/nest)
  - [nest.physics.ucdavis.edu](http://nest.physics.ucdavis.edu)
Thank you for your attention!
Backup Slides
Heavy Nuclei

- Expanded the $\alpha$-model to include scattering events with heavy ions
- Again, contradictory data sets, splits the difference

Absolute Scintillation Yields in Liquid Argon and Xenon for Various Particles
Japanese Journal of Applied Physics, Volume 41, Part 1, Number 3A

LET dependence of scintillation yields in liquid xenon
M. Tanaka, et. al. 2001
Boron-8

- Great agreement with LZ TDR $^8$B spectrum.
- Not a look-up table!
NESTv2 accurately reproduces NR and ER bands. X10 detector file example provided with NESTv2. Easy to change and add your own detector!