A New Tool for \((\alpha,n)\) Yield Calculations and Its Implications for DEAP-3600

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DEAP-3600 Collaboration
(Low Radioactivity Techniques 2017)
The Importance of Neutron Backgrounds: WIMP Detectors

I'm a WIMP!
The Importance of Neutron Backgrounds: $0\nu\beta\beta$ Detectors
High Sensitivity → Must Understand Neutron Backgrounds!
Sources of Neutrons: Cosmogenic
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- $\mu$
- $\nu$
- $n$
- $\mu$
- $n$
- $\nu$
- $\mu$
- $n$
- $\nu$
Sources of Neutrons: Radiogenic

- Due to nuclear reactions in detector components
- Depends on levels of $^{238}\text{U}$, $^{235}\text{U}$, and $^{232}\text{Th}$ contamination
- Produced by
  - Fission
  - Direct emission
  - $(\alpha,n)$ reaction
Sources of Neutrons: Radiogenic

$^{238}\text{U}$ Fission:
$1.1 \times 10^{-6}$ n/s/Bq

$^{210}\text{Tl}$ Direct Neutron Emission:
$1.5 \times 10^{-8}$ n/s/Bq
Sources of Neutrons: Radiogenic: The $\alpha, n$ Reaction

- Rate depends on concentration of all $\alpha$-emitting contaminants in decay chains
- Depends on composition of material
- Need to calculate $\alpha, n$ yield of each material

($\alpha, n$) Reaction
Neutron Calculator Based On TALYS

See paper at arXiv:1702.02465 (Submitted to NIM A)
Download: github.com/shawest/neucbot
NeuCBOT

• Calculates \((\alpha, n)\) yields and neutron energy spectra for given decay chains or lists of \(\alpha\) energies in arbitrary materials

• Complete stopping power database generated by SRIM code (Ziegler et al.)

• Complete database of \((\alpha, n)\) cross sections and neutron spectra for all naturally occurring isotopes for \(\alpha\) energies below 10 MeV
  – Integrates with TALYS to further extend database
NeuCBOT User Input

- Material Composition
  - List of chemical symbols, isotopes (0 for natural abundance), and percent mass

- α Energy List
  - Energy in MeV followed by percent probability

```
# Example Semi-Heavy Water
H 1 5.3
H 2 10.5
O 0 84.2
```

```
# Example Alpha Source
5 100
6 50
```
NeuCBOT User Input

• Material Composition
  – List of chemical symbols, isotopes (0 for natural abundance), and percent mass

• Isotope List
  – Isotope symbol followed by percent branching ratio
  – Looks up α decay data from ENSDF database

# Example Semi-Heavy Water
H 1 5.3
H 2 10.5
O 0 84.2

# Th232 Decay Chain Alpha-emitters
Th232 100
Th228 100
Ra224 100
Rn220 100
Po216 100
Bi212 35.94
Po212 64.06
NeuCBOT Calculations

\[ Y(T_n) = \sum_\alpha P_\alpha \sum_m \frac{N A C_m}{A_m} \] 

\[ \sum \sigma_m(T'_\alpha, T_n) \Delta T'_\alpha \]

\[ T'_\alpha \in \{ T_\alpha, T_\alpha - \Delta T'_\alpha, \ldots, 0 \} \]

\[ S(T'_\alpha) \]

\[ \alpha \] energy (from user input + ENSDF)

\[ \alpha \] probability (from user input + ENSDF)

Target nucleus mass number

Outgoing neutron energy

Target nucleus mass fraction in material (user input)

Cross section (from TALYS)

Mass stopping power (from SRIM)
NeuCBOT Calculations

\[ Y(T_n) = \sum_{\alpha} P_\alpha \sum_{m} \frac{N_A C_m}{A_m} \sum_{T'_\alpha} \frac{\sigma_m(T'_\alpha, T_n)}{S(T'_\alpha)} \Delta T'_\alpha \]

- \( \alpha \) probability (from user input + ENSDF)
- Target nucleus mass fraction in material (user input)
- Cross section (from TALYS)
- Mass stopping power (from SRIM)
- \( \alpha \) energy (from user input + ENSDF)
- Target nucleus mass number
- Outgoing neutron energy
NeuCBOT Calculations

\[ Y(T_n) = \sum_{\alpha} P_\alpha \sum_m \frac{NAC_m}{A_m} \sum \frac{\sigma_m(T'_\alpha, T_n)}{S(T'_\alpha)} \Delta T'_\alpha \]

- \( \alpha \) probability (from user input + ENSDF)
- Target nucleus mass fraction in material (user input)
- Cross section (from TALYS)
- Outgoing neutron energy
- Target nucleus mass number
- \( \alpha \) energy (from user input + ENSDF)
- Mass stopping power (from SRIM)
NeuCBOT Calculations

\[
Y(T_n) = \sum_\alpha P_\alpha \sum_m \frac{N_A C_m}{A_m} \sum \sigma_m(T', T_n) \Delta T'_\alpha \\
\text{Outgoing neutron energy}
\]

\[
T'_\alpha \in \{T_\alpha, T_\alpha - \Delta T'_\alpha, \ldots, 0\}
\]

\[
\text{Target nucleus mass number}
\]

\[
\alpha \text{ energy (from user input+ENSDF)}
\]

\[
\text{Target nucleus mass fraction in material (user input)}
\]

\[
\text{Cross section (from TALYS)}
\]

\[
\text{Mass stopping power (from SRIM)}
\]
Validation

- TALYS and the TENDL database have been extensively validated, themselves
- Compare to measured (α,n) yields
- Compare to SOURCES-4C?
  - Extended cross section data from JENDL library and EMPIRE code
Validation: General agreement, but NeuCBOT Slightly Systematically Higher
Validation: NeuCBOT and SOURCES spectra agree well
Future Developments

- Web interface
- Calculate gamma spectrum in coincidence with neutrons
- Options to interface with nuclear databases instead of TALYS
  - e.g. ENDF, JENDL, etc.
DEAP-3600

- Located at SNOLAB
- Over 3 tonnes LAr
- Viewed by 255 PMTs
- 50 cm of acrylic buffer between PMTs and LAr
- Inside water tank
- muon veto
DEAP-3600 Neutron Background

- Radioactive contamination measured via ex-situ $\gamma$-counting
- Use NeuCBOT to estimate yield of each primary component
- Simulate neutrons in GEANT4 to estimate how many may look like a WIMP
## DEAP-3600 Neutron Yields

<table>
<thead>
<tr>
<th>NeuCBOT</th>
<th>n/s/Bq</th>
<th>U238 upper</th>
<th>U238 lower</th>
<th>U235</th>
<th>Th232</th>
</tr>
</thead>
<tbody>
<tr>
<td>Borosilicate Glass</td>
<td></td>
<td>3.93E-06</td>
<td>1.76E-05</td>
<td>2.56E-05</td>
<td>2.43E-05</td>
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<tr>
<td>Acrylic</td>
<td></td>
<td>2.19E-07</td>
<td>9.72E-07</td>
<td>1.42E-06</td>
<td>1.33E-06</td>
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<tr>
<td>Invar</td>
<td></td>
<td>2.06E-12</td>
<td>2.58E-07</td>
<td>1.84E-07</td>
<td>1.08E-06</td>
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<tr>
<td>TPB</td>
<td></td>
<td>3.15E-07</td>
<td>1.35E-06</td>
<td>1.96E-06</td>
<td>1.84E-06</td>
</tr>
<tr>
<td>Polyethylene</td>
<td></td>
<td>2.52E-07</td>
<td>1.09E-06</td>
<td>1.58E-06</td>
<td>1.49E-06</td>
</tr>
<tr>
<td>Polystyrene</td>
<td></td>
<td>3.01E-07</td>
<td>1.29E-06</td>
<td>1.88E-06</td>
<td>1.77E-06</td>
</tr>
<tr>
<td>Stainless Steel</td>
<td></td>
<td>1.31E-09</td>
<td>5.52E-07</td>
<td>4.42E-07</td>
<td>1.96E-06</td>
</tr>
<tr>
<td>Argon</td>
<td></td>
<td>8.82E-08</td>
<td>1.41E-05</td>
<td>1.72E-05</td>
<td>2.64E-05</td>
</tr>
</tbody>
</table>
DEAP-3600 Neutron Rates

• Expect 143,000±4,000 neutrons/year
  – Predominantly in PMT glass

• The vast majority of these neutrons will fail to make it into the LAr
  – Geometric factors
  – Blocked by acrylic buffer

• Monte Carlo indicate that ~18.6 n/year will produce a signal in the LAr above 11 keVee
  – Most will be outside ROI and fiducial cuts
Life of a DEAP Neutron
Life of a DEAP Neutron
Can we use these coincidences to tag neutrons and constrain the neutron rate?
In Situ Neutron Search: Strategy

Neutron scatter (Nuclear recoil)

Capture $\gamma$ scatter (Electron recoil)

Random background (Electron recoil)

$O(100 \text{ us})$
1) Identify Neutron Scatter Candidates

- Neutron scatter
- Backgrounds:
  - α decay
  - Cherenkov
  - Etc.
2) Identify Neutron Capture Candidates

- $^1\text{H}(n,\gamma)^2\text{H}$ (2.2 MeV)
- $^{40}\text{Ar}(n,\gamma)^{41}\text{Ar}$ (6.1 MeV)

Backgrounds:
- Uncorrelated backgrounds with high energy $\gamma$-rays

Capture $\gamma$ scatter (Electron recoil)
3) Measure Uncorrelated ER Rate

- Backgrounds:
  - Uncorrelated backgrounds with high energy $\gamma$-rays

Random background (Electron recoil)
AmBe Calibration: Clear Neutron Capture Signals

Total Energy Deposited by Gammas Following a Nuclear Recoil

2.2 MeV from $^1\text{H}(n,\gamma)^2\text{H}$
AmBe Calibration: Clear Neutron Capture Signals

Total Energy Deposited by Gammas Following a Nuclear Recoil

6.1 MeV from $^{40}\text{Ar}(n,\gamma)^{41}\text{Ar}$
AmBe Calibration: Detect NR-ER Coincidence was 19.3% Efficiency

Efficiency of Detecting Neutron Capture Gammas in AmBe Data

- Efficiency on the y-axis
- Photoelectrons Detected in Nuclear Recoil on the x-axis
In Situ Neutron Search: Saw no neutron captures

- Looked at 109 days of data in DEAP-3600
- Saw 0 NR-ER pairs
  - Require: NR above 11 keVee
  - Require: ER above 1.9 MeV
- Expected 1.4 false coincidences
Upper limit on neutron event rate consistent with prediction

Feldman-Cousins upper limit (90% C.L.): < 25.5 n/year scatter in LAr above 11 keV_{ee}

Consistent with NeuCBOT prediction of 18.6 n/year!
Conclusion

- We have developed a new tool for calculating \((\alpha,n)\) yields in arbitrary materials
  - NeuCBOT: https://github.com/shawest/neucbot
- Validated against measured yields and SOURCES-4C calculations
- Predict ~18.6 n/year in DEAP-3600
- *In situ* limits constrain rate of neutrons in LAr to < 25.5 n/year
  - Consistent with NeuCBOT predictions
End
AmBe Calibration: Capture signals reliably follow neutrons by 1 ms