A Standard Framework for Reactor Neutrino Flux Calculation

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7/23/2022
Snowmass CSS, 2022

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Challenges in Reactor Neutrino Predictions

- Challenges
  - Antineutrinos come from thousands of beta decaying branches produced from reactors
  - Predicting neutrinos involves summarizing beta branches with unknown factors

- Problems:
  - Reactor neutrino spectra directly measured are different from the predictions
  - Reactor neutrino predictions are essential to model dependent neutrino studies and applications neutrino detection

Fission products

Neutrinos yielded from fission products for different isotopes

7/23/22
Goals

• **Scientific and Application needs:**
  - Reactor neutrino flux prediction for neutrino physics (CEvNS, model dependent BSM studies)
  - References for reactor monitoring, e.g. advanced reactors

• **Structural motivations:**
  - Standardize the neutrino flux prediction
  - A publicly available tool – with modularity and completeness
  - Easy-to-use software with full documentation
  - Create a format for human-readable input data, e.g. reactor evolution & nuclear data
  - Lower the ‘barrier to entry’ for the neutrino physicists to generate and compare predictions

Expand the energy range

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Calculation Of Neutrino FLUX

• Predictions are based on
  • Summation β spectra, or
  • Conversions of reactor β measurements
  • Direct reactor neutrino measurements

• Modular data and theory in software
  • Easy to update
  • Cross-mode comparison
  • Customizable modules

COMING SOON
The Software Structure

- Prediction with three different modes (two functional, one in development)
- Flexible time dependent reactor model inputs
- Coded in Python3, can be installed and imported in analyzers own calculations

![Diagram of the software structure with two modes: 'Summation' Mode and 'β-conversion' Mode.]

Based on nuclear DBs

**'Summation' Mode**
- CFY-DB
- F(t), \( v_{\text{mf}}(t) \)
- β-tally Engine
- \( p_\beta \)
- Summation Engine
- \( S_{\nu}(E,t) \)
- β-spectrum Engine
- β-DB

Based on reactor β spectra

**'β-conversion' Mode**
- Conversion-DB
- F(t)
- Conversion Engine
- \( S_{\nu}(E,t) \)
- Reactor Input
- \( v_{\text{mf}}(t) \)
- Summation of unmeasured contributions

\( v_{\beta}(t) \), \( v_{\text{ne}}(T) \), \( v_{\text{mf}}(t) \)
Flexible Inputs of Different Modes

- User input: Time dependent fission fragments or composition of a reactor
- Summation:
  - The β branch info parsed from databases such as ENSDF, ENDF, JEFF
  - Nuclear DBs are parsed into xml formats for accessibility
  - Updated β decay measurement with TAGS
- Conversion:
  - β spectrum measurements of fission isotopes
  - Converted neutrino flux from beta spectra
Beta Spectrum Calculation

• A common $\beta$ spectrum generator for the summation and conversion modes.

• Use of state-of-art theoretical calculation with BSG [CPC 240 (2019) 152].

• Some corrections are important for low energy beta spectra.

• Spectrum shape corrections are built to be freed up to test model uncertainties affected by specific parameters.

<table>
<thead>
<tr>
<th>Item</th>
<th>Effect</th>
<th>Formula</th>
<th>Magnitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Phase space factor</td>
<td>$pW(W_0 - W)^2$</td>
<td>Unity or larger</td>
</tr>
<tr>
<td>2</td>
<td>Traditional Fermi function</td>
<td>$F_0$</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Finite size of the nucleus</td>
<td>$L_0$</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Radiative corrections</td>
<td>$R$</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Shape factor</td>
<td>$C$</td>
<td>$10^{-1}-10^{-2}$</td>
</tr>
<tr>
<td>6</td>
<td>Atomic exchange</td>
<td>$X$</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Atomic mismatch</td>
<td>$r$</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Atomic screening</td>
<td>$S$</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Shake-up</td>
<td>See item 7</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Shake-off</td>
<td>See item 7</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Isovector correction</td>
<td>$C_I$</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Recoil Coulomb correction</td>
<td>$Q$</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>Diffuse nuclear surface</td>
<td>$U$</td>
<td>$10^{-3}-10^{-4}$</td>
</tr>
<tr>
<td>14</td>
<td>Nuclear deformation</td>
<td>$D_{FS} &amp; D_C$</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>Recoiling nucleus</td>
<td>$R_N$</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>Molecular screening</td>
<td>$\Delta S_{Mol}$</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>Molecular exchange</td>
<td>Case by case</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>Bound state $\beta$ decay</td>
<td>$\Gamma_b/\Gamma_c$</td>
<td>Smaller than $1 \cdot 10^{-4}$</td>
</tr>
<tr>
<td>19</td>
<td>Neutrino mass</td>
<td>Negligible</td>
<td></td>
</tr>
</tbody>
</table>

CPC 240 (2019) 152
Summation

• Fission products counted from
  • ENDF/B-VIII, or JEFF-3.3 on default.

• Uncertainty:
  • Beta model uncertainty
  • Beta branch fraction
  • Fission product yield
  • Fission fragments

• Default assumption:
  • Missing branching assumed as single-branch non-forbidden decay to the ground state
  • Missing information of spin-parity changes are assumed as non-forbidden
Beta-conversion

- Beta data used is the ILL fission beta spectra of U235, Pu239, and Pu241.
- Beta data are fitted with virtual branches generated by BSG
  - Branch number is of user choice
- Uncertainty:
  - Data uncertainty randomized for MC to calculate the covariance matrix
- Unmeasured contributions are corrected with summation calculations
Calculation Output with Selected Conditions

- Beta spectrum calculation for selected isotopes, with respect to atom number, end point energy, contributions to the total neutrino flux, etc.

<table>
<thead>
<tr>
<th>Isotope</th>
<th>percent-contribution</th>
<th>Q-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Br-90</td>
<td>5.6 * 10^{-3}</td>
<td>10.959 MeV</td>
</tr>
<tr>
<td>As-86</td>
<td>5.5 * 10^{-3}</td>
<td>11.541 MeV</td>
</tr>
<tr>
<td>Rb-100</td>
<td>3.5 * 10^{-3}</td>
<td>13.574 MeV</td>
</tr>
<tr>
<td>Rb-96</td>
<td>2.1 * 10^{-3}</td>
<td>11.571 MeV</td>
</tr>
<tr>
<td>As-84</td>
<td>1.3 * 10^{-3}</td>
<td>10.094 MeV</td>
</tr>
<tr>
<td>In-130</td>
<td>9.7 * 10^{-4}</td>
<td>10.249 MeV</td>
</tr>
<tr>
<td>Rb-97</td>
<td>3.8 * 10^{-4}</td>
<td>10.432 MeV</td>
</tr>
<tr>
<td>Br-92</td>
<td>2.7 * 10^{-4}</td>
<td>12.537 MeV</td>
</tr>
<tr>
<td>Cd-131</td>
<td>1.4 * 10^{-4}</td>
<td>12.87 MeV</td>
</tr>
<tr>
<td>Ga-80</td>
<td>1.2 * 10^{-4}</td>
<td>10.38 MeV</td>
</tr>
<tr>
<td>Ga-84</td>
<td>1.1 * 10^{-4}</td>
<td>13.69 MeV</td>
</tr>
<tr>
<td>Ga-82</td>
<td>6.3 * 10^{-5}</td>
<td>12.484 MeV</td>
</tr>
<tr>
<td>In-132</td>
<td>6.2 * 10^{-5}</td>
<td>14.14 MeV</td>
</tr>
<tr>
<td>Rb-98</td>
<td>4.0 * 10^{-5}</td>
<td>12.054 MeV</td>
</tr>
<tr>
<td>Br-93</td>
<td>3.1 * 10^{-5}</td>
<td>11.09 MeV</td>
</tr>
</tbody>
</table>
Combined/compared prediction with two modes

- Results and reference spectra of two modes can be added and modified for combined prediction
- Different modes use common theories and nuclear databases, allow direct cross-mode comparisons

Simple combination between the summation and conversion results
Summation Calculation with Correlated Fission Products

- Correlation/covariance matrices of fission fragments or beta branches can be given as additional input in the summation.

Input U235 FPY correlation
j.adt.2021.101441

235U neutrino spectrum with mockup correlation matrix
Coming soon

• Software is under beta testing and documentation
• Aim to release the software and publish documentations of CONFLUX to the community in 2022
• Neutrino experiment-based prediction
  • Tabulated neutrino data from fissile isotopes
  • Combined calculation with the summation mode to fit specific reactor
Potential Scientific Output

• Neutrino spectra and flux prediction on different reactor types:
  • Reactor CEvNS detection
  • BSM neutrino physics

• Contribute to the nuclear data community
  • Cross-database comparisons
  • Search for deviations to prioritize beta decay measurements to be revisited

• Studies on the reactor simulation for near field reactor survey

…
Summary

• CONFLUX is a framework of reactor neutrino prediction for neutrino physicists.
• The goal is to provide calculation modules with standard, easy-to-access nuclear data and state-of-art theories of beta decays.
• Analyzers can use flexible reactor inputs and corrections.
• The framework is under construction and able to calculate reactor neutrino flux with time dependent reactor inputs.
• CONFLUX is a tool that can be utilized to provide a wide range of scientific output for the nuclear and particle physics communities, important contributions to neutrino frontier topics.
Thank you!
Backup – examples of inputs

Input:

• Time dependent reactor model with fission fractions (all three modes):

```json
{{"time_0", "power_0", {"235_Thermal", [frac, d_frac]}, {"238_fast", [frac, d_frac]}, {...}, ...},
...
{{"time_n", "power_n", {"235_Thermal", [frac, d_frac]}, {"238_fast", [frac, d_frac]}, {...}, ...}}
```

• Time dependent radioactive source model with simulated beta branches (summation mode only):

```json
{{"time_0", "power_0", {"beta_branch_0", [frac, d_frac]}, {"beta_branch_1", [frac, d_frac]}, ...},
...
{{"time_n", "power_n", {"beta_branch_0", [frac, d_frac]}, {"beta_branch_1", [frac, d_frac]}, ...}}
```