Snowmass 2021 - Letter of Interest

High-Resolution Multiphysics Reactor Modeling for the Antineutrino Source Term

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This LOI seeks to motivate the use of advanced approaches to whole-core reactor modeling for determining the antineutrino source term. We briefly outline the broader context and impact of this activity and then review the recent trends in reactor modeling and simulation. We illustrate how state-of-the-art multiphysics reactor simulation codes could be used to provide a more detailed picture of the reactor antineutrino source to better support analysis and development of models for neutrino physics. It is suggested that future experimental programs based on reactor antineutrino sources examine the benefits of such advanced modeling and simulation capabilities, which may lead to their adoption in future precision antineutrino physics studies.

Neutrino Frontier Topical Groups:
(NF07) Nuclear Safeguards and Other Applications
(NF09) Artificial neutrino sources
(NF10) Neutrino Detectors

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Scientific Motivation

A detailed understanding of the antineutrino flux and energy spectra requires a detailed understanding of the state of the nuclear reactor. To minimize sources of uncertainty and potentially confounding errors in measurements and predictions, the state of the nuclear reactor should be as well characterized as possible. This would enable neutrino researchers to have increased confidence that discrepancies between prediction and measurement are not due to modeling approximations – but rather gaps in our current understanding of neutrino physics. Therefore, most areas of neutrino research, and especially those that seek to improve upon the precision of antineutrino spectrum and flux measurements such as Daya Bay [1] and PROSPECT [2], can benefit from high-fidelity, whole-core reactor calculations that resolve reactor detail (such as fission rates and isotopic compositions) at the sub-pin scale (*e.g.*, $<$1 cm) and incorporate multiphysics feedback.

Some of the specific high-impact scientific goals are shared with another synergistic LOI [3] submitted to Snowmass 2021 and include:

HEP Science Drivers

- Generating precise data-driven and theory-based flux and spectrum models for all fission isotopes
- Resolving flux discrepancies between reactor antineutrino predictions and measurements
- Resolving spectral discrepancies between LEU antineutrino predictions and measurements

Nuclear Science and Application Drivers

- Enabling nuclear reactor monitoring using $\overline{\nu}_e$ detectors
- Advancing nuclear databases and calculations used for nuclear science and nuclear energy

Current Reactor Modeling and Simulation Trends

Modeling trends for reactor antineutrino sources show that they have not yet utilized high-fidelity, multiphysics tools. Many of the published methodologies for the reactor simulation use quite simplified models such as a point reactor [4] or subdomains of the reactor – typically a lattice or assembly [5]. More recently, international researchers have developed high-fidelity Monte Carlo neutronics models of research reactors [6], but these models still lack consistent fidelity in the coupled physics – specifically, thermal-hydraulics and nuclide transmutation.

Required Enabling Capabilities

These scientific goals are already achievable given the current maturity of simulation tools for light water reactors (LWRs). The use of advanced multiphysics models can provide a much more representative and rigorous picture of the state of a nuclear reactor. However, instead of enabling "capabilities", there needs to be *dedicated* cooperation of members of the neutrino physics community, the reactor physics community, the neutrino detector community, and the commercial nuclear power plant operators such that the predictive power of such advanced approaches for the reactor neutrino source term calculations can be accessed.

Specific Approaches to Address Modeling Needs

To enhance the overall predictive power for the antineutrino signature we propose to develop, adapt, and utilize the coupled multiphysics methodologies that can integrate the neutronics, thermal hydraulics, and fission product decay aspects of the reactor state evolution.

An example of such multiphysics approach is VERA-CS [7] developed over the last 10 years in the CASL (Consortium for the Advanced Simulation of Light Water Reactors) program, the U.S. DOE's Energy Innovation Hub. The use of VERA-CS requires the development of a capability to post-process data already computed by VERA-CS to produce the antineutrino spectra. VERA-CS combines the neutronics code MPACT, the thermal-hydraulics code CTF [8], and ORIGEN [9] from SCALE [10]. Together, these tools resolve the temperature, reaction rates, and compositions at the sub-pin level. Generally, VERA-CS tracks around 300 isotopes for 3 different radial regions and 50 axial segments in all 50,952 fuel rods in the core,

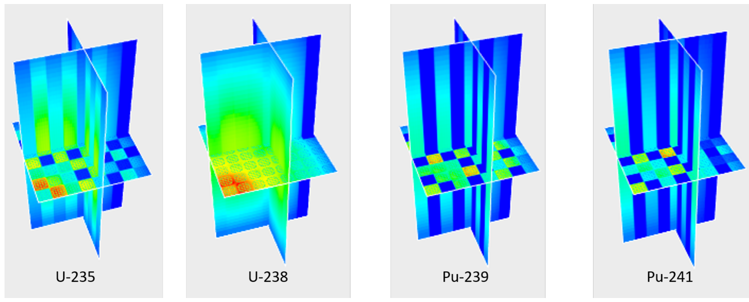

FIG. 1. VERA-CS predicted antineutrino source by fissile species for MOX fueled core

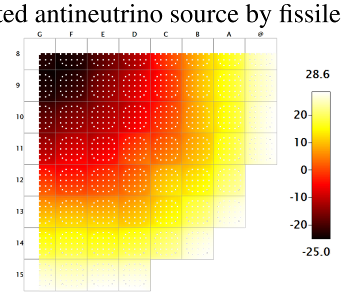

FIG. 2. Change in antineutrino source from hot zero power to full power

and it is capable of tracking the full >2200 nuclide chains available in ORIGEN. Recently, the ability to predict sub-pin level reaction rates was validated against a fresh fuel in a critical facility [11]. The validation of the fuel composition as a function of burnup relies heavily on ORIGEN's validation, but we have separately performed comparisons to discharge fuel compositions measured from the Takahama-3 reactor [12]. VERA-CS has also been used and validated against over 100 plant cycles for a variety of PWR reactor types. It was also used to predict the start-ups of Watts Bar Unit 2, and the new AP1000's Sanmen units 1 and 2. VERA-CS is quite possibly the most extensively validated high-fidelity, multiphysics simulation tool for nuclear reactors [13]. In Figure 1 we show the estimated end of cycle reaction rates for the four principal fissile isotopes: ^{235}U, ^{238}U, ^{239}Pu, and ^{241}Pu. This clearly illustrates that a point reactor model is insufficient as the different locations in the reactor will be producing neutrinos from the different fissile isotopes. This also has implications on the detected spectra since the distance to a near-field detector may be substantially different for the different fissile sources. Furthermore, Figure 2 shows how the fission distribution changes as a function of power level due to multiphysics feedback. Consequently, the dominant fissile isotope (*e.g.*, fresh fuel, burned fuel, or MOX fuel) for which neutrinos may be detected could change with power level given the appropriate core loading.

We propose that initial efforts focus on LWRs. The first reason for this is that LWRs are already operating and generating neutrinos that can support the high-fidelity physics measurements. Furthermore, as described earlier, the associated simulation tools are very mature and well validated. Therefore, LWRs offer the best technology to advance neutrino research for both measurement and simulation. While we acknowledge that many advanced reactors likely pose a greater safeguards risk, that technology is still in development and the associated simulation tools are not as mature. Consequently, an intensive research effort focused on advanced reactors for neutrino physics purposes is likely premature at this point.

In conclusion, we feel it is imperative to support work to integrate the modern multiphysics reactor simulation methodology for LWRs into the precision neutrino physics studies. This will allow for more refined calculations of information that is necessary to determine the spatially dependent neutrino source in the reactor given its current state. These activities will require close collaboration and coordination between multiple expert communities and is complementary to the need to improve the isotope-level understanding of the antineutrino flux and spectrum [3]. Therefore, we invite the Snowmass community to consider the potential benefits of improving the reactor modeling and adopting high-fidelity whole-core reactor simulation methods for neutrino source term characterization.

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