FSNN Theory Workforce LRP 2022

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I. BACKGROUND

The persistence of open questions about the observed universe, related to the generation of the baryon asymmetry, the origin and nature of neutrino mass, and the identity of dark matter, suggests that the Standard Model (SM) of fundamental interactions is not a complete description of nature and makes the search for new physics a crucial enterprise. As the 2015 NSAC Long Range Plan [1] recognizes, nuclear physics plays a prominent role in this enterprise through a "targeted program of fundamental symmetries and neutrino research" that aims to challenge the Standard Model and shed light on the outstanding questions. Assessing the impact of nuclear and neutrino probes of beyond the SM (BSM) physics requires accurate input from nuclear theory.

The fundamental symmetries community within nuclear physics has played a special role in strengthening ties to particle physics and astrophysics, helping to build appreciation for the continued relevance of the entire field. Our contributions to topics such as neutrino mass and lepton number conservation and the structure of neutron stars and the dynamics of their mergers are widely recognized.

However, the growing complexity of the problems the subfield is tackling and the absence of an institutional center to support the field present challenges to theory workforce development for Fundamental Symmetries, Neutrons, and Neutrinos (FSNN). There are two major issues:

1. **Multi-scale problem:** Understanding the imprint of new physics in hadronic and nuclear environments is a multi-scale problem, involving energies that range from very small nuclear energy level splittings to typical QCD energy scales, to the electroweak scale and ultimately, up to the scale of new physics. Tackling these problems requires broad expertise, in areas that include

    (a) **Phenomenology & Effective Field Theory (EFT)**: This capability is essential for understanding the impact of nuclear probes of BSM physics in the broader context of cosmology and high-energy physics. Work is required to compare the sensitivity of nuclear probes to complementary collider and cosmological probes, and to build towers of effective field theories that bridge theories at different energy scales, with different degrees of freedom. Perturbative EFTs such as the Standard Model EFT and its low-energy version (LEFT) allow for the evolution of BSM interactions from the scale of new physics down to low-energy scales at which QCD is nonperturbative. At nuclear scales, hadronic EFTs can be used to systematically organize nuclear interactions induced by BSM physics.

    (b) **Hadronic Physics**: Matching the hadronic operators to quark and gluon operators requires a coordinated effort between lattice QCD and the EFTs. Great progress has been made in recent years, with single nucleon matrix elements determined with a full uncertainty budget of a few percent from lattice QCD. Applications to fundamental symmetry pose a new set of challenges: the calculation of four-point functions (for nucleon EDMs and radiative corrections to β decays), the complicated renormalization of higher-dimensional operators on the lattice, the calculation of nucleon-nucleon scattering amplitudes in the presence of symmetry-violating interactions (needed for studies of neutrinoless double-beta decay and of time-reversal and parity violation in nuclei).

    (c) **Nuclear Structure & Reactions**: Accurate calculations of nuclear structure and reactions with quantified theoretical uncertainties are required to disentangle new physics from nuclear effects. Microscopic many-body methods based on EFT and on phenomenological interactions and currents provide us with viable paths for achieving this goal. In the past few years, there has been tremendous progress towards the evaluation of nuclear matrix elements relevant to the fundamental symmetries program, including those for single and double beta decay, EDMs, hadronic parity violation, and lepton-nucleus scattering. The challenge is to develop a comprehensive theory of nuclear dynamics in the wide range of energy and momentum probed by the experimental programs in FSNN.

The success of the FSNN field relies on the synergy of all three theoretical components outlined above; all have strong overlap with other important areas of nuclear science, namely cold QCD [2] and nuclear structure and astrophysics [3]. Synergies with theory efforts in high-energy physics and astrophysics (in the form of collaborative projects and career opportunities for students and postdocs) have been and will continue to be critical for the health of the field. Constructing synergistic programs can be challenging because of barriers that range from non-homogeneous training backgrounds to separate funding streams.

2. **Lack of an institutional center:** Other subfields in nuclear physics are generally built around the community's major user facilities, JLab, RHIC, FRIB, and thus have institutional centers that recognize their importance and support theory-workforce development. In addition to serving as hubs for experimental activities, these national facilities bring experimentalists and theorists together on a recurring schedule. The FSNN community plays a role in the major user facilities, but it has not been a central focus of any of them. As a consequence, the community has had to depend on general-purpose theory centers to support its collaborative activities; these have included the Institute for Nuclear Theory (INT) and focused organizations such as the Amherst Center for Fundamental Interactions (ACFI) and the Network for Neutrinos, Nuclear Astrophysics, and Symmetries (N3AS). But in contrast to FRIB, JLab, and RHIC, these university-based theory centers provide fewer opportunities for interaction with experimentalists and do not have workforce-development programs that can help young researchers find faculty positions.

These challenges mean that the FSNN theory community, while successful, is more fragmented than other communities. Fragmentation limits the community's ability to fully realize the broad FSNN experimental program, creating an obstacle to progress for the whole FSNN field, not just theory. Opportunities to remedy these problems are outlined in the next section.

II. RECOMMENDATIONS

A robust theoretical research program is essential for taking full advantage of the FSNN experimental program. **We recommend a set of initiatives aimed at nurturing and growing the nuclear theory program in FSNN in order to keep pace with the growing experimental effort.** Here are important elements of this program:

1. The funding agencies have recognized the importance of supporting collaborative work on high-impact multifaceted problems, such as those described here, that require the integration of phenomenology & EFT, lattice QCD, and nuclear structure & reactions. New opportunities have been created through **Hubs, Topical Collaborations [4], Physics Frontier Centers [5], and SciDAC programs**. Recognizing the particular importance of these programs to FSNN, **we ask for increased support, including more opportunities to sustain successful collaborations beyond the five-year periods common in these programs**;

2. We call for the timely identification and implementation of mechanisms to enlarge and support the FSNN theoretical workforce at universities and national laboratories, with procedures and best practices that develop and sustain a diverse, equitable, welcoming, and inclusive workforce and culture. The collaborative opportunities described above have significantly increased the

participation of graduate students and postdocs in FSNN. Because FSNN draws talent from boundaries shared with particle and astrophysics, the pool of young scientists is unusually broad and diverse. For the same reason, these young people can compete in broad faculty searches. Yet the lack of faculty bridging programs suited to FSNN is inhibiting success. **We ask the agencies to create a faculty bridging program for FSNN theory.**

Strong endorsements for increased efforts in FSNN theory along these lines have appeared in several 2022 FSNN white papers [6]. An NSAC subcommittee could be charged with considering these endorsements and the two recommendations above and finding appropriate ways to address the subfield's needs.

NSAC subcommittee recommendations could also spur the formation of a national consortium with elements analogous to those of the NP FRIB Theory Alliance [7] and HEP Neutrino Theory Network (NTN) [8]. This consortium could work with the funding agencies to administer the FSNN faculty bridge program. It could also help existing and future Hubs, Topical Centers, and Frontier Centers coordinate their activities in workforce development at all levels. In partnership with the INT and other visitor centers, these organizations could extend their coordination to the field's workshops, including those promoting experimental participation.

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[1] Reaching for the horizon: The 2015 long range plan for nuclear science, `https://www.osti.gov/biblio/1296778`.
[2] 2022 NSAC Long-Range Plan Town Hall Meeting on Hot and Cold QCD, `https://indico.mit.edu/event/538/`.
[3] 2022 NSAC Long-Range Plan Town Hall Meeting on Nuclear Structure, Reactions and Astrophysics, `https://indico.phy.anl.gov/event/22/`.
[4] Topical Collaboration on Nuclear Theory for Double Beta Decay and Fundamental Symmetries, `https://a51.lbl.gov/~0nubb/webhome/`.
[5] Network for Neutrinos, Nuclear Astrophysics, and Symmetries (N3AS), `https://n3as.berkeley.edu/`.
[6] LRP FSNN: 2022 White Papers, `https://indico.phy.ornl.gov/event/209/page/99-white-papers`.
[7] FRIB Theory Alliance, `https://fribtheoryalliance.org/`.
[8] Neutrino Theory Network, `https://ntn.fnal.gov/`.