Nuclear Matrix Elements for BSM Searches from Lattice QCD

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Nuclei make up the majority of the visible matter in the Universe; understanding their emergence from the underlying theory of the strong interaction is thus a fundamental challenge bridging nuclear and particle physics. From neutrino physics to dark matter searches, nuclear targets are critical to many fundamental experiments that are being used to search for previously unknown aspects of physics. Interpreting the results of these experiments with fully controlled uncertainties necessitates a better theoretical understanding of nuclear targets. Large-scale numerical calculations using lattice QCD (LQCD) will allow us to address this challenge and achieve a quantitative connection between the Standard Model (SM) and nuclear phenomenology, opening new directions in the quest to interpret the complexities of nuclear physics and support efforts to use nuclei to reveal fundamental aspects of nature and probe beyond-Standard-Model (BSM) physics.

Over the last decade, our collaboration (the NPLQCD Collaboration) has pioneered efforts to extend the scope of LQCD to nuclei and has undertaken the first calculations of the structure and interactions of light nuclei directly from the Standard Model, albeit at larger-than- physical values of the quark masses. We have performed the first LQCD calculations of nucleon-nucleon and hyperon-nucleon interactions, and the spectrum of the light nuclei and hypernuclei. More recently, we have calculated the magnetic properties of light nuclei, finding, remarkably, that the magnetic moments (in units of natural magnetons) are nearly independent of the quark masses over a large interval; this suggests that nucleons are the relevant degrees of freedom inside nuclei even at unphysically heavy quark masses. With the same suite of calculations, we determined the cross section for the low-energy inelastic nuclear reaction $np \to d\gamma$, the first nuclear reaction in the evolution of the universe. Our result reproduced the precisely known experimental cross-section, lending credence to our ability to control systematic uncertainties in these first LQCD calculations of nuclear processes. Extending these calculations to axial currents, we have computed the rate of the proton-proton fusion process that initiates the solar burning cycle in the Sun and separately the rate of tritium β-decay. Matrix elements of scalar and tensor currents that are of potential relevance in dark-matter direct detection experiments and searches for electric dipole moments have also been calculated, with scalar matrix elements in light nuclei seen to differ significantly from the impulse approximation in which the nucleons are treated as independent. Furthermore, second-order interactions with the axial currents that determine the rate of the $\beta\beta$-decay processes of nuclei have also been studied, revealing previously-overlooked contributions in the nuclear matrix elements that enter these processes.

In the coming years, we anticipate that these first studies will be revisited to determine the target quantities at the physical values of the quark masses and address systematic uncertainties in the lattice method that are not as yet fully quantified. Additional quantities will also become accessible, either through expansion of the scope of LQCD calculations or through a close connection between LQCD calculations in light nuclei and effective field theories and phenomenological models used in nuclear many-body methods. The latter approaches, in which nuclear EFTs or phenomenological nuclear models are matched to LQCD inputs, extend the reach of LQCD to larger nuclei and promise a systematically improvable connection of nuclear matrix elements to the SM, even in large nuclei.

Examples of where LQCD calculations of nuclear matrix elements will have impact on intensity frontier experiments in the coming years are:

- Dark-matter direct detection experiments. The scalar couplings of nuclei quantify the contribution of explicit chiral symmetry breaking to nuclear masses, and define nuclear σ-terms. In the simplest spin-independent case, the σ-terms govern the interaction probabilities of many particle dark matter candidates with nuclei in direct-detection experiments.

- Precision atomic isotope shift spectroscopy. While it is matrix elements in large nuclei such as Xenon that are important in the dark-matter context, the same scalar operators are relevant in precision atomic isotope shift spectroscopy in light nuclei that can be directly addressed in LQCD.

- $\mu 2e$ conversion experiment and other searches for lepton-flavour violation (LFV). The low energy manifestation of the breaking of lepton-flavour symmetry (an accidental symmetry of the SM broken by neutrino masses) in many BSM scenarios, is the generation of higher-dimension operators (in the framework of SM effective field theory (SMEFT)) such as $\overline{q}\Gamma q \overline{e}\Gamma' \mu$ that involve quark degrees of freedom ($\Gamma^{(\prime)}$ represents various different spin and flavour structures). Since the $\mu 2e$ experiment looks for LFV in the field of an Aluminium nucleus, nuclear matrix elements of the hadronic parts of these operators for various Dirac and flavour structures are needed for interpretation of such experiments.

- Searches for permanent electric dipole moments (EDMs). The tensor current matrix elements encode the quark EDM contributions to the EDMs of light nuclei and thus comparison to experimental searches sets bounds on BSM sources of CP violation. Given that the CP violation in the weak interaction is insufficient to generate the observed matter-anti-matter asymmetry of the universe (assuming exact CPT invariance and baryon–anti-baryon symmetry of the initial conditions), many experiments have sought to measure permanent EDMs as evidence for such sources. Even with a successful measurement of a permanent EDM, fully disentangling the sources of CP violation requires multiple observables, and experiments searching for EDMs of a range of different light nuclei are in the planning stages.

- Double-β decay nuclear matrix elements. Observation of neutrinoless double-β decay would shed light on the nature of neutrinos and would unambiguously show that the neutrino is a Majorana fermion, i.e., it is its own antiparticle. Although solely observing a decay will mark a major discovery, without a proper isolation of the nuclear matrix elements contributing to the rate of this decay, little insight can be gained into the BSM mechanism mediating this transition. LQCD calculations of few nucleon transition matrix elements such as $nn \to ppe\overline{\nu}$ will provide critical input into the nuclear many-body approaches that can address the phenomenologically important nuclei. LQCD is currently the only known way to determine some of the required inputs.

- Nuclear n-$\overline{n}$ annihilation searches. Searches performed in large-volume underground detectors provide competitive bounds on $B - L$ violation than neutron beam experiments, but are more difficult to interpret theoretically. To make best use of such experimental limits (or future observations), requires nuclear transition matrix elements induced by 6-quark operators occurring at dimension-9 in SMEFT. Significant theoretical advances are required for these calculations to be useful when there are multiple hadrons in the final state.

LQCD has had major impact in numerous BSM searches, in particular in the heavy-flavour sector, over the last two decades. It is anticipated that with continued effort in LQCD and related EFT and nuclear many-body approaches, new results will similarly provide critical theoretical inputs for of some or all of the above examples to test for, and ultimately identify the origin of, BSM physics. Further details can be found in a recent review [1].

Topical Groups:

■ (TF05) Lattice Gauge Theory
■ (RF3) Fundamental Physics in Small Experiments
■ (RF4) Baryon and Lepton Number Violating Processes
■ (RF5) Charged Lepton Flavor Violation (electrons, muons and taus)
■ (RF6) Dark Sector Studies at High Intensities
■ (NF6) Neutrino cross sections
■ (CompF2) Theoretical Calculations and Simulation

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