Bridging particle and nuclear physics for neutrinoless double beta decay with EFTs

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Abstract

The interpretation of current and future searches of neutrinoless double beta decay ($0\nu\beta\beta$) at the ton-scale and beyond in terms of mechanisms for lepton number violation is a multi-scale problem, involving the new physics, hadronic, and nuclear scales. Effective field theory (EFT), complemented by lattice QCD and nuclear many body methods, provides the bridge between the relevant scales. We outline recent progress, challenges, and possible future directions in this area that interfaces particle and nuclear theory.

Neutrinoless double beta decay ($0\nu\beta\beta$) is the process where two neutrons inside an atomic nucleus are transmuted into two protons and two electrons without the emission of neutrinos. An observation of this process would indicate that lepton number (L) is not a good symmetry of nature and that the neutrino mass has a Majorana component, implying that the mass eigenfields are self-conjugate. Current experimental limits are very stringent [1–12], e.g. $T^{0\nu}_{1/2} > 1.07 \times 10^{26}$yr for ^{126}Xe [5], with next-generation ton-scale experiments aiming for one to two orders of magnitude improvement.

The simplest interpretation of $0\nu\beta\beta$ experiments assumes that lepton-number violation (LNV) is due to the exchange of light Majorana neutrinos. However in various beyond-the-SM (BSM) scenarios other sources of LNV exist that can induce $0\nu\beta\beta$. For example, in left-right symmetric models, apart from the exchange of a light Majorana neutrino, there appear contributions from the exchange of heavy neutrinos and charged scalars. In other scenarios there may be light right-handed (sterile) neutrinos with masses much lower than the electroweak scale. While a single nonzero $0\nu\beta\beta$ measurement can be attributed to any LNV interaction, in principle various LNV sources can be disentangled by measurements of different isotopes, the angular or energy distributions of the outgoing electrons, or by correlating with other observables (including $pp \to ee + 2$ jets at colliders [13, 14]) provided sufficient theoretical control can be achieved.

Given the breadth of mechanisms and scales associated with LNV sources, the phenomenology of $0\nu\beta\beta$ is best tackled by EFT methods, describing in a systematically improvable way the LNV dynamics both at high energy and at hadronic and nuclear scales. In this 'end-to-end' EFT approach one describes at a given energy scale the LNV dynamics in terms of appropriate degrees of freedom. In order to accommodate the presence of new light particles, such as sterile neutrinos, the Standard Model field content may need to be extended when formulating the EFT. We stress here that the EFT approach, in conjunction with improved lattice QCD and many-body methods, is the only path towards reaching controlled uncertainties in $0\nu\beta\beta$ matrix element calculations [15], which currently plague the interpretation of $0\nu\beta\beta$ in terms of LNV parameters (e.g. Majorana masses of left-handed neutrinos).

The end-to-end EFT framework generalizes previous approaches [16–19] and has been developed in several recent papers [20–25]. This multi-pronged approach connects the scale Λ of LNV to nuclear scales through various steps:

1. The use of the Standard Model EFT, extended to include light sterile neutrinos, to link the scale Λ of LNV to the hadronic scale $\Lambda_\chi \sim O(1)$ GeV, where non-perturbative QCD effects arise. This step is by now mature: the operator basis, to which any underlying model can be matched, is known up to dimension nine [26–28] and the renormalization group evolution of the operators under strong interactions is known.

2. The matching of the quark-gluon level EFT to hadronic EFTs such as Chiral Perturbation Theory (χPT), applicable to the meson and single nucleon sector, and Chiral or Pionless EFT in the multi-nucleon sector. This step can be performed consistently in the strong and weak sectors of the theory, which in the case of interest here involves $\Delta L = 2$ transition operators. The form of the transition operators is known to leading order in the hadronic EFT expansion for all underlying LNV mechanisms [21, 23], and sub-leading corrections are also known for most mechanisms. The matching procedure typically requires the introduction of hadronic interactions that are short-range compared to the typical nuclear scale and have effective couplings which encode non-perturbative strong-interaction physics. In what follows, we refer to these effective couplings as low-energy constants (LECs).

3. The use of Lattice QCD (LQCD) to determine the relevant LECs, including the ones controlling $\Delta L = 2$ transition operators needed to predict $0\nu\beta\beta$. This step involves matching a given hadronic or few-body amplitude computed in LQCD to the corresponding expression in the hadronic EFT. This is a relatively new area of research (for reviews see [29,30]). Recent activity has focused on the mesonic (e.g. $\pi^-\pi^- \to ee$) LECs of relevance for both TeV LNV mechanisms and light Majorana neutrino exchange for $0\nu\beta\beta$ [31–34]. Addressing the challenges associated with two-nucleon (such as $nn \to ppee$) and multi-nucleon matrix elements in LQCD is an active area of research [35–37]. At the same time, EFT calculations for LNV transitions should be tailored to use the same infrared regulators as the lattice calculations to optimize the matching procedure.

4. The solution of the nuclear many-body problem for nuclei of experimental interest, through *ab initio* nuclear structure methods, relying on QCD-rooted strong potentials and $\Delta L = 2$ transition operators. These calculations are in their infancy for nuclei of experimental interest such as ^{76}Ge [38,39], and can be benchmarked in lighter nuclei where first-principles methods are available [40, 41].

While progress has been made in the past few years, we identify below a set of open questions that will require further study in the future:

- What is the connection between $0\nu\beta\beta$ and LNV observables at present (ATLAS, CMS, FASER) and future (EIC, ShIP, MATHUSLA) collider experiments? What is the best strategy to explore this connection: should UV-complete models be considered or can one apply EFTs or simplified models in which the SMEFT is complemented with new degrees of freedom at the electroweak scale?

- What are the $0\nu\beta\beta$ constraints on realistic models with sterile neutrinos in the KeV-GeV mass range (e.g. 3+3 models), which are relevant to low-scale leptogenesis scenarios? How are such scenarios affected by new sterile neutrino interactions at the TeV scale, which appear as higher-dimensional operators in the EFT? How do LECs and nuclear matrix elements depend on the sterile neutrino masses?

- In case of a positive signal at ton-scale experiments, what is the best strategy to pinpoint the origin of LNV? Can the EFT framework provide a roadmap for this?

- In the problem at hand, the matching to hadronic EFTs involves non-perturbative parameters, the LECs. Notably, the LECs appearing at leading order in $0\nu\beta\beta$ for both light Majorana neutrino exchange and TeV scale LNV are currently unknown [21, 23]. LECs could be determined in the future by the analysis of suitable $\Delta I = 2$ observables, as well as direct calculations using analytic and lattice QCD methods.

- On the nuclear structure side, a major future thrust will involve the analysis of nuclear matrix elements with ab-initio methods and a validation of the EFT expansion. In particular, do many-body correlations preserve the EFT hierarchy of the two-body transition operators, which have their largest effects right around the nuclear Fermi surface?

A full assessment of the impact of $0\nu\beta\beta$ searches for particle physics necessarily requires bridging scales all the way down to the nuclear scale. EFT provides the framework for doing this. With this LOI, our aim has been to recall recent progress and outline the challenges lying ahead.

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