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Relativistic chiral effective field theory for neutrinoless double beta decay

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The relativistic chiral EFT approach is introduced to improve the existing estimates of the $nn \to ppee$ amplitude by including contributions up to next-to-leading order. The estimated $nn \to ppee$ amplitude, $|\mathcal{A}_{0\nu}| = 0.0209(7)$ MeV^{-2} at the kinematics $|\boldsymbol{p}_i| = 25$ MeV, $|\boldsymbol{p}_f| = 30$ MeV, can be used to determine the leading order decay operator in nuclear-structure calculations. The approach is also applied to calculate the ground-state-to-ground-state $nn \to ppee$ matrix element at $m_\pi \simeq 806$ MeV on a finite-size lattice, showing promising agreement with the recent first lattice QCD simulation.

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1. Introduction

Neutrinoless double beta decay ($0\nu\beta\beta$) is a beyond-Standard-Model weak process, where a nucleus decays to its neighboring nucleus by turning two neutrons into two protons, emitting two electrons but no corresponding antineutrinos [1]. It signals lepton number violation (LNV) and, if observed, would confirm that neutrinos are of Majorana nature [2] and help to settle the mass hierarchy of neutrinos. Therefore, it becomes one of the top priorities in the field of nuclear and particle physics, and stimulates worldwide experimental searches [3]. However, the theoretical calculations so far suffer from considerable uncertainties of nuclear matrix elements (NMEs) [4], which hamper the interpretation of current experimental limits on $0\nu\beta\beta$ and potential future discoveries.

The calculation of $0\nu\beta\beta$ NMEs requires a collaboration of methods at multiple energy scales, from the high energies at which LNV originates all the way down to nuclear energies. Effective Field Theory (EFT) provides the bridge between these scales, by expanding observables and Lagrangians in the ratios of the important energy scales. The Standard Model EFT enables a systematic treatment of different LNV mechanisms in terms of the operators involving neutrinos, electrons, and u and d quarks [5]. The standard mechanism of $0\nu\beta\beta$ corresponds to the leading dimension-five operator [6]. However, these quark-level operators cannot be directly applied to nuclear-structure calculations. They need to be converted into hadronic operators by nuclear EFTs, to construct the neutrino potential in the nucleon-pion degrees of freedom, so that this neutrino potential can be used for nuclear-structure calculations of NMEs [7–14].

The uncertainty of the neutrino potential has recently received wide attention from the community, as the nuclear EFT analyses [15, 16] have revealed a potential leading-order (LO) contribution from a previously unrecognized contact decay operator. Various nuclear-structure calculations indicate that its contribution could be comparable to the standard long-range nuclear matrix elements [17–19]. However, the size of the contact coupling $g_\nu^{\rm NN}$ is highly uncertain due to the absence of LNV data. This introduces a significant uncertainty in the calculations of the NMEs and, thus, in the interpretation of the large-scale searches for $0\nu\beta\beta$ decay.

The $nn \to ppee$ process is the elementary subprocess of $0\nu\beta\beta$ in nuclei. Its amplitude is required to determine the LO contact coupling $g_\nu^{\rm NN}$ and, thus, plays a key role in addressing the uncertainty of the contact decay operator. The LO estimation of the $nn \to ppee$ amplitude was given by the generalized Cottingham formula [20, 21]. This approach introduces phenomenological inputs for elastic intermediate states and neglects inelastic contributions, resulting in uncertainties that need to be further scrutinized. In the meantime, a first-principle calculation of the $nn \to ppee$ process from lattice QCD (LQCD) is being pursued energetically by the community [22]. Recently, the first LQCD simulation of the $nn \to ppee$ process was carried out by NPLQCD Collaboration [23]. Although it is performed at the unphysical pion mass $m_\pi \simeq 806$ MeV, it provides new possibilities to benchmark the nuclear EFTs and models for $nn \to ppee$ amplitudes.

Recently, the relativistic chiral EFT approach was developed in Refs. [24, 25] to provide predictions of the $nn \to ppee$ amplitude up to next-to-leading order (NLO).. This is possible thanks to the fact that the $nn \to ppee$ amplitude can be renormalized without the unknown LO contact decay operator. The approach was also extended to calculate the ground-state-to-ground-state $nn \to ppee$ matrix element at $m_\pi \simeq 806$ MeV on a finite-size lattice [26].

2. Relativistic chiral effective field theory

For two-nucleon (NN) scattering processes, the relativistic scattering equation is employed to calculate the NN scattering amplitudes,

$$\begin{aligned} T(\boldsymbol{p}_f, \boldsymbol{p}_i) &= V(\boldsymbol{p}_f, \boldsymbol{p}_i) + \int \frac{\mathrm{d}^3 k}{(2\pi)^3} V(\boldsymbol{p}_f, \boldsymbol{k}) G_0(\boldsymbol{k}; E) T(\boldsymbol{k}, \boldsymbol{p}_i), \\ G_0(\boldsymbol{k}; E) &= \frac{M^2}{\boldsymbol{k}^2 + M^2} \frac{1}{E + 2M - 2\sqrt{\boldsymbol{k}^2 + M^2} + \mathrm{i}0^+}, \end{aligned} \tag{1}$$

where E is the total kinetic energy, M the nucleon mass, and $\boldsymbol{p}_f$ ($\boldsymbol{p}_i$) the two nucleons' final (initial) momentum in the center-of-mass frame. This relativistic scattering equation is obtained by employing time-ordered perturbation theory without nonrelativistic reduction [27]. For the ${}^1S_0$ channel, the strong potential up to NLO takes the form [28]

$$V(\boldsymbol{p}', \boldsymbol{p}) = V^{(0)} + V^{(1)} = C - \frac{g_A^2}{4 f_\pi^2} \frac{m_\pi^2}{m_\pi^2 + \boldsymbol{q}^2} + \left(\delta C + D \frac{\boldsymbol{p}'^2 + \boldsymbol{p}^2}{2} \right) \tag{2}$$

with the momentum transfer $\boldsymbol{q} = \boldsymbol{p}' - \boldsymbol{p}$, the axial coupling $g_A = 1.27$, the pion decay constant $f_\pi = 92.2$ MeV, and the pion mass $m_\pi = 138.03$ MeV. Here, the LO part includes the momentum-independent contact term C and the static one-pion-exchange potential, and the NLO part includes a shift δC to the LO contact term and a momentum-dependent contact term D. The LO NN amplitude $T^{(0)}$ is obtained by iterating $V^{(0)}$ nonperturbatively in Eq. (1). To achieve renormalization beyond LO, the NLO contribution $T^{(1)}$ is included perturbatively on top of the LO NN amplitude [28].

We focus on the $nn \to ppee$ process in the ${}^1S_0$ channel, which dominates at low energies and is the only channel relevant to the unknown contact term. The renormalized $nn \to ppee$ amplitude with all contributions up to NLO reads [25]

$$\begin{aligned} \mathcal{A}_{fi}^{\mathrm{NLO}} = -\rho_{fi} (&V_\nu + V_\nu G_0 T^{(0)} + T^{(0)} G_0 V_\nu + T^{(0)} G_0 V_\nu G_0 T^{(0)} \\ &+ T^{(1)} G_0 V_\nu + V_\nu G_0 T^{(1)} + T^{(1)} G_0 V_\nu G_0 T^{(0)} + T^{(0)} G_0 V_\nu G_0 T^{(1)}), \end{aligned} \tag{3}$$

where ρ_{fi} is a phase space factor, and $T^{(0)}$ and $T^{(1)}$ denote the LO and NLO pieces of NN scattering amplitudes, respectively. They are determined by the np scattering phase shifts up to $E_{\mathrm{lab}} = 100$ MeV. For the neutrino potential V_ν, the LO contact term is not needed for renormalization of the $nn \to ppee$ amplitude in the relativistic chiral EFT approach [29]. As a result, the neutrino potential has no unknown low-energy constants (LECs), and only receives contributions from the static neutrino exchange [30],

$$V_\nu(\boldsymbol{q}) = \frac{\tau_1^+ \tau_2^+}{\boldsymbol{q}^2} \left\{ 1 + 2 g_A^2 \left[1 + \frac{m_\pi^4}{2(\boldsymbol{q}^2 + m_\pi^2)^2} \right] \right\}. \tag{4}$$

To enable direct comparison with the LQCD calculations, in Ref. [26], we implement our relativistic chiral EFT approach at LO using the same LQCD conditions [23]. The momentum modes are discretized according to the periodic boundary condition,

$$\boldsymbol{q} \in \mathbb{R}^3 \to \boldsymbol{q} \in \frac{2\pi}{L} \mathbb{Z}^3, \boldsymbol{q} \neq \boldsymbol{0}, \tag{5}$$

with lattice size $L = 4.6$ fm. We integrate out the pions in the relativistic chiral EFT and use the physical value of the axial coupling constant $g_A = 1.27$. The LO LEC C in Eq. (2) is determined by the ${}^1S_0$ NN ground-state energy from LQCD calculations at $m_\pi = 806$ MeV.

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3. Predictions for the $nn \to ppee$ amplitude

Figure 1 depicts the $nn \to ppee$ amplitudes at $(p_i, p_f) = (25, 30)$ MeV predicted by the relativistic chiral EFT, as a probability distribution from the Bayesian analysis of both the LECs and EFT truncation errors [25]. The relativistic predictions of the $nn \to ppee$ amplitude are compared to the nonrelativistic LO results from the generalized Cottingham model [20]. The LO nonrelativistic and relativistic results agree with each other within the estimated errors. However, the LO nonrelativistic result lies outside the 68% Bayesian confidence interval of the NLO prediction by relativistic chiral EFT, and is smaller than the maximum-likelihood estimate at NLO by about 10%.

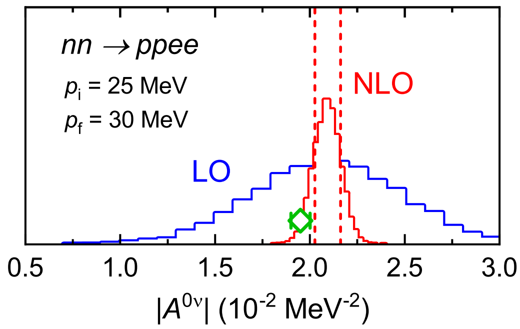

Figure 1: Probability density distributions of the $nn \to ppee$ amplitude, obtained from the LO and NLO relativistic chiral EFT in Ref. [25]. The dashed vertical lines indicate the 68% Bayesian confidence intervals at NLO. The empty diamond depicts the LO estimate from the generalized Cottingham model [20].

Figure 2 compares the LO relativistic EFT prediction [26] and the LQCD simulation result [23] at $m_\pi = 806$ MeV with lattice size $L = 4.6$ fm. For the $^1S_0$ NN ground-state energy E_{nn}, there exists a discrepancy between the older ($E_{nn} \simeq -17$ MeV) [31] and the latest ($E_{nn} \simeq -3$ MeV) [32] results by NPLQCD Collaboration. The discrepancy is suspected to be due to the misidentification of "false plateaus" in the older works. Both the older and the latest results for E_{nn} from Refs. [31, 32] are used to as input of EFT, yielding two EFT predictions. The LO relativistic EFT prediction, obtained with the latest LQCD E_{nn}, agrees well with the result from direct LQCD simulation.

4. Conclusion

The relativistic chiral EFT approach has been developed to provide an improved estimate of the $nn \to ppee$ amplitude, which we quote [25],

$$|\mathcal{A}_{0\nu}| = 0.0209(7)\ \text{MeV}^{-2}, \tag{6}$$

at the kinematics $|\boldsymbol{p}_i| = 25$ MeV, $|\boldsymbol{p}_f| = 30$ MeV. It can be readily used to determine the contact coupling g_ν^{NN} in the nonrelativistic nuclear-structure calculations of nuclear matrix elements.

In the future, the estimated $nn \to ppee$ amplitude can be further refined by including higher-order inelastic corrections [33]. Moreover, future systematic comparisons between the EFT matrix elements and the LQCD ones could stringently validate the relativistic chiral EFT approach on the $nn \to ppee$ amplitude, once the latter are available at more pion masses or lattice sizes. Finally, it

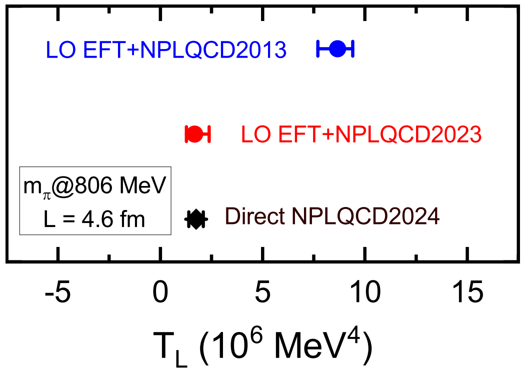

Figure 2: LO relativistic EFT predictions of the $nn \to ppee$ amplitude [26] compared to the direct LQCD simulation [23] at m_π = 806 MeV with lattice size L = 4.6 fm. Two LO EFT predictions are shown, obtained using two LQCD results of the $^1S_0$ NN ground-state energy as inputs [31, 32], respectively.

would also be interesting to carry out relativistic nuclear-structure calculations [34–37] of nuclear matrix elements using the relativistic chiral $0\nu\beta\beta$ decay operator.

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