Short-distance nuclear matrix elements for $0\nu\beta\beta$

Will Detmold, David Murphy, Patrick Oare, Phiala Shanahan

Department of Physics, Massachusetts Institute of Technology

Introduction

Neutrinoless double beta decay ($0\nu\beta\beta$) is a reaction which, if observed, would give direct evidence of lepton-number violating physics beyond the Standard Model (SM). This work studies the unphysical pion decay:

$$\pi^- \longrightarrow \pi^+ e^- e^-.$$

The $0\nu\beta\beta$ amplitude is typically split into two parts:

- A **long-distance** contribution describing electroweak physics[1].
- A **short-distance** contribution describing the BSM physics.

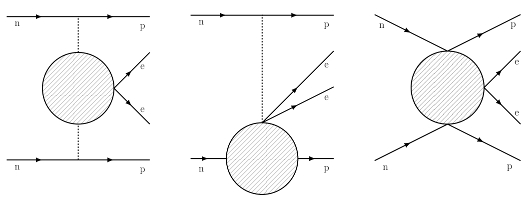
This project will compute the short-distance amplitude.

Background

The short-distance contributions in the SM EFT are mediated by dimension six 4-quark operators with charge 2. The operator basis used in the pionic decay is[2]:

$$\mathcal{O}_1 = (\overline{u}\gamma^\mu P_L d)[\overline{u}\gamma_\mu P_R d]$$
$$\mathcal{O}_2 = (\overline{u}P_L d)[\overline{u}P_L d] + (L \leftrightarrow R)$$
$$\mathcal{O}_3 = (\overline{u}\gamma^\mu P_L d)[\overline{u}\gamma_\mu P_L d] + (L \leftrightarrow R)$$
$$\mathcal{O}_1' = (\overline{u}\gamma^\mu P_L d][\overline{u}\gamma_\mu P_R d)$$
$$\mathcal{O}_2' = (\overline{u}P_L d][\overline{u}P_L d) + (L \leftrightarrow R)$$

In chiral perturbation theory (χPT), the nucleonic $0\nu\beta\beta$ amplitude $n^0 n^0 \to p^+ p^+ e^- e^-$ is mediated through pion exchange via the following diagrams:



The low-energy coefficients (LECs) governing this decay in χPT are determined via knowledge of the matrix elements $\langle \pi^+ | \mathcal{O}_i | \pi^- \rangle$ from lattice QCD.

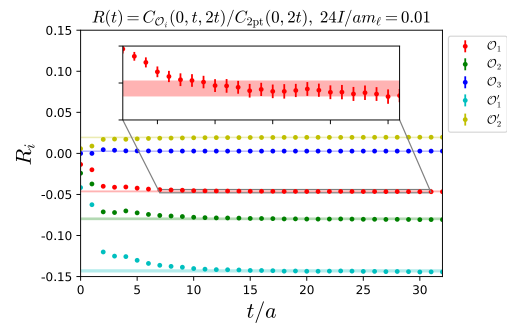
Lattice Calculation

This analysis uses 5 ensembles of 2+1 flavor domain wall fermions (Shamir kernel) with the Iwasaki gauge action.

Matrix elements of the five short-distance operators are computed between pion states. They are extracted from the large-time behavior of the three-point correlator:

$$\mathcal{C}_{\mathcal{O}}(t_-, t_x, t_+; \vec{p}) = \sum_{\vec{x}} e^{i\vec{p}\cdot\vec{x}} \langle 0 | T\{\chi_{\pi^+}(t_+)\mathcal{O}(x)\chi_{\pi^-}(t_-)\}|0\rangle$$
$$\longrightarrow A_\pi \langle \pi^+ | \mathcal{O} | \pi^- \rangle e^{-m_\pi |t_+ - t_-|}.$$

This exponential dependence is cancelled by dividing out by the time-averaged two-point function to form the ratio R, which is fit to a constant to extract $\langle \pi^+ | \mathcal{O}_i | \pi^- \rangle$.



Renormalization

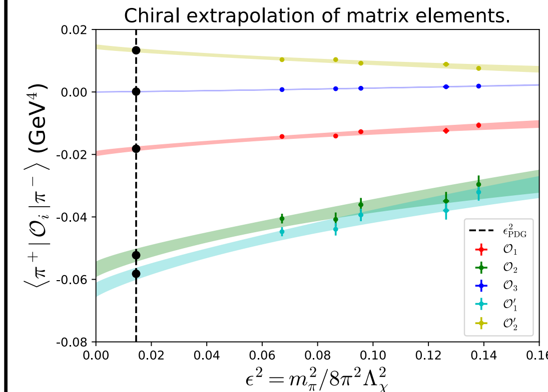
To connect to phenomenology, the operators must be renormalized. The renormalization coefficients (RCs) are computed non-perturbatively in the RI/sMOM scheme and converted to $\overline{\mathrm{MS}}$ with perturbative input[3]. In the RI/sMOM scheme, the RCs $\mathcal{O}_i^{\mathrm{R}} = \mathcal{Z}_{ij}\mathcal{O}_j^{(0)}$ are defined as:

$$\frac{1}{\mathcal{Z}_q^2}\mathcal{Z}_{ij}\Gamma_j\Big|_{\mathrm{sym}} = \Gamma_i^{(\mathrm{tree})}$$

where Γ is the amputated four-point function for each operator in the basis, and symmetric kinematics are used for the quark lines and current insertion. This work is currently in progress.

Chiral Extrapolation

Results from each of the five ensembles are extrapolated to the physical point using results from chiral perturbation theory. The fit forms contain three independent coefficients α_i, β_i, c_i for each operator, of which β_i is used to constrain the LECs.



Results

The preliminary results for the extrapolated matrix elements and the fit coefficients for each operator are as follows. Final results are forthcoming, as the RCs are expected to modify this data at the 10% level.

Operator	α_i (fm^{-2})	β_i	c_i	$\langle \pi^+ \vert \mathcal{O}_i \vert \pi^- \rangle$ (GeV^4)
$\mathcal{O}_1$	-7.2(2.2)	-1.727(56)	-0.168(386)	-0.01818(54)
$\mathcal{O}_2$	3.2(2.7)	-4.97(20)	-0.27(45)	-0.0523(19)
$\mathcal{O}_3$	43.6(2.8)	0.633(16)	1.40(56)	$1.248(26) \times 10^{-4}$
$\mathcal{O}_1'$	-7.3(2.2)	-5.55(18)	-0.41(38)	-0.0582(17)
$\mathcal{O}_2'$	0.6(2.6)	1.270(49)	-0.28(44)	0.01334(47)

References:

1. W. Detmold, D. Murphy. Neutrinoless Double Beta Decay from Lattice QCD: The Long-Distance $\pi^- \to \pi^+ e^- e^-$ Amplitude. arXiv:2004.07404 [hep-lat] (2020).
2. V. Cirigliano *et al.*, Lattice QCD Inputs for Nuclear Double Beta Decay. DOI 10.1016/j.ppnp.2020.103771 (2020).
3. Nicholson, A. *et al.*, Heavy Physics Contributions to Neutrinoless Double Beta Decay from QCD. Phys Rev Lett 121, 172501 (2018).