Neutrinoless double beta decay of hyperons in covariant chiral perturbation theory

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I.Introduction

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Nuclear double beta decays

• $2\nu 2\beta$ -decay

[M.G.Mayer, Phys. Rev. 48, 512(1935)]







✓ Experimentally Observed

- [A.s.Barabash, Phys.Rev.C81,035501(2010)]
- $^{A}_{Z}X \rightarrow {}^{A}_{Z+2}Y + 2e^{-} + 2\bar{\nu}_{e}$

• $0\nu 2\beta$ -decay

[Furry, Phys, Rev. 56, 1184(1939)]



$$\overset{\Lambda}{}_{Z}^{A}X \to \overset{\Lambda}{}_{Z+2}^{A}Y + 2e^{-}$$

$$T_{\frac{1}{2}} > 3.8 \times 10^{26} \ {\rm yr}$$

[KamLAND-Zen Collaboration,arXiv:2406.11438

[hep-ex] (2024)]

✓ Lepton number violation
 ✓ Majorana nature of
 neutrinos
 ✓ Neutrino mass scale and

hierarchy

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Nuclear matrix element

Nuclear matrix elements(NMEs) encode the impact of the nuclear structure on the decay half-life, crucial to interpreting the experimental limits on the effective neutrino mass.

$$(T_{\frac{1}{2}}^{0\nu})^{-1} = G^{0\nu} |M^{0\nu}|^2 |m_{\beta\beta}|^2$$

(Light Majorana neutrino exchange mechanism)



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EFT at various energy scales

[Cirigliano, et al. JHEP12(2018)]



Derivation of $0\nu 2\beta$ decay operator in hadron level

• N²LO in ChPT: $\pi^{-}\pi^{-} \rightarrow e^{-}e^{-}$

[Cirigliano,et al, PhysRevC.97.065501(2018)]

- Dimension-7 operators in chiral EFT Cirigliano, Dekens, Mereghetti, Walker-Loud, JEHP1708.09390(2020)
- Dimension-9 operators in SMEFT: $K^- \rightarrow \pi^+ e^- e^-$ [Liao, Ma and Wang, JHEP03(2020)]

Hyperon $0\nu2\beta$ decay

Advantage:

- Nuclear $0\nu 2\beta$ decays $\Delta S = 0$; Hyperon $0\nu 2\beta$ decays $\Delta S \neq 0$.
- Hyperon factory @ BESIII & STCF: $J/\Psi \rightarrow \Sigma \bar{\Sigma}$.

Measurement by BESIII Collaboration: [Phys.Rev.D103,052011(2021)]

$$\mathcal{B}(\Sigma^- \to p e^- e^-) < 6.7 \times 10^{-5}, \quad \mathcal{B}(\Sigma^- \to \Sigma^+ X) < 1.2 \times 10^{-4}$$

2 Based on loops involving virtual baryon and Majorana neutrino states:

$$\mathcal{B}(\Sigma^- \to p e^- e^-) \sim 10^{-31}, \quad \mathcal{B}(\Sigma^- \to \Sigma^+ X) \sim 10^{-35}$$

[H.F Li Phys.Rev.D76, 116008 (2007)] [H.F Li Phys.Rev.D87,036010 (2013)]

$$\mathcal{B}(\Sigma^- \to p e^- e^-) \sim 10^{-23}$$

Based on the MIT bag model:

II.Calculation in BChPT

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Neutrinoless double beta decay in ChPT

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- ChPT is an effective field theory of QCD at low energy based on chiral symmetry at hadronic level.
- A first glance: from quarks to hadrons



Hyperon $0\nu 2\beta$ decay in BChPT

 \bullet Description of $0\nu 2\beta$ decay of hyperons at one-loop level in ChPT



• The chiral effective Lagrangian relevant to the decay process:

$$\mathcal{L}_{eff} = \mathcal{L}_{MB}^{(1)} + \mathcal{L}_{M}^{(2)} + \mathcal{L}_{\Delta L=2}$$

• The LO baryon-meson interaction Lagrangian is given by

$$\mathcal{L}_{\mathrm{MB}}^{(1)} = \mathrm{Tr}\left[\bar{B}\left(i\not\!\!D - m\right)B\right] - \frac{D}{2}\left\langle\bar{B}\gamma^{\mu}\gamma_{5}\left\{u_{\mu}, B\right\}\right\rangle - \frac{F}{2}\left\langle\bar{B}\gamma^{\mu}\gamma_{5}\left[u_{\mu}, B\right]\right\rangle$$

• The LO chiral Lagrangian for purely mesonic interaction reads

$$\mathcal{L}_{M}^{(2)} = \frac{F_{0}^{2}}{4} \operatorname{Tr}[(D_{\mu}U)^{\dagger}D^{\mu}U] + \frac{F_{0}^{2}}{4} \operatorname{Tr}[U^{\dagger}\chi + U\chi^{\dagger}]$$

• The covariant derivative:

$$[D_{\mu},X]=\partial_{\mu}X+[\Gamma_{\mu},X]$$

• Chiral connection:

$$\Gamma_{\mu} = \frac{1}{2} \left\{ u^{\dagger} (\partial_{\mu} - ir_{\mu})u + u(\partial_{\mu} - il_{\mu})u^{\dagger} \right\}$$

• The so-called chiral vielbein:

$$u_{\mu} = i \left\{ u^{\dagger} (\partial_{\mu} - ir_{\mu})u - u(\partial_{\mu} - il_{\mu})u^{\dagger} \right\}$$

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• Left-handed current: • Right-handed current:

$$l_{\mu} = -2\sqrt{2}G_F T_+[\bar{\nu}_L \gamma_{\mu} \ell_L] + \text{h.c.} \qquad r_{\mu} = 0$$

$$T_{+} = \begin{pmatrix} 0 & V_{ud} & V_{us} \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} = \frac{V_{ud}}{2}(\lambda_1 + i\lambda_2) + \frac{V_{us}}{2}(\lambda_4 + i\lambda_5)$$

Vij denote the elements of the Cabibbo-Kobayashi-Maskawa quark-mixing matrix.

Low-energy dimension-5 operator for the $\Delta L=2$ Lagrangian [Cirigliano,JHEP12(2017)082]

$$\mathcal{L}_{\Delta L=2} = -\frac{1}{2} (m_{\beta\beta})_{ij} (\nu_{L,i}^T C \nu_{L,j} + \bar{\nu}_{L,i} C^{\dagger} \bar{\nu}_{L,j}^T)$$



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Due to the presence of the λ matrices in the Lagrangian, we can express the vertex rules as a product of the Gell-Mann part and the Dirac part



Feynman Rules: with weak current

$$= \frac{1}{2} \{-\gamma^{\mu} f_{abc} + \gamma^{\mu} \gamma_{5} (iDd_{abc} - Ff_{abc})\}$$

$$= \frac{1}{2} \{-\gamma^{\mu} f_{abc} + \gamma^{\mu} \gamma_{5} (iDd_{abc} - Ff_{abc})\}$$

$$= \frac{1}{\sqrt{2}F_{0}} \{\gamma^{\mu} f_{cde} f_{abe} - \gamma^{\mu} \gamma_{5} f_{cde} (Dd_{abe} - Ff_{abe})\}$$

$$= -\frac{1}{4} F_{0} q^{\mu} \delta_{ab}$$

Amplitude structure



Lorentz decomposition of hadronic tensor

$$H_{\mu\nu} = \bar{u}(p_2) \left\{ \sum_{i=1}^{34} (\mathcal{H}_V^i \mathcal{O}_{V,\mu\nu}^i + \mathcal{H}_A^i \mathcal{O}_{A,\mu\nu}^i) \right\} u(p_1)$$



$$\begin{array}{c} \mathcal{O}_{V,\mu\nu}^{13} = p_{1\nu}k_{2\mu} \\ \mathcal{O}_{V,\mu\nu}^{14} = k_{1\mu}k_{2\nu}k_{1} \\ \mathcal{O}_{V,\mu\nu}^{15} = k_{1\nu}k_{2\mu}k_{1} \\ \mathcal{O}_{V,\mu\nu}^{16} = k_{1\mu}k_{1\nu}k_{1} \\ \mathcal{O}_{V,\mu\nu}^{16} = k_{2\mu}k_{2\nu}k_{1} \\ \mathcal{O}_{V,\mu\nu}^{17} = k_{2\mu}k_{2\nu}k_{1} \\ \mathcal{O}_{V,\mu\nu}^{19} = p_{1\mu}p_{1\nu}k_{1} \\ \mathcal{O}_{V,\mu\nu}^{19} = k_{1\nu}p_{1\mu}k_{1} \\ \mathcal{O}_{V,\mu\nu}^{20} = p_{1\mu}k_{2\nu}k_{1} \\ \mathcal{O}_{V,\mu\nu}^{22} = p_{1\nu}k_{2\mu}k_{1} \\ \mathcal{O}_{V,\mu\nu}^{22} = p_{1\nu}k_{2\mu}k_{1} \\ \mathcal{O}_{V,\mu\nu}^{23} = p_{1\mu}\gamma_{\nu} \end{array}$$

$$\begin{array}{c} \mathcal{O}_{V,\mu\nu}^{24} = p_{1\nu}\gamma_{\mu} \\ \mathcal{O}_{V,\mu\nu}^{25} = k_{1\mu}\gamma_{\nu} \\ \mathcal{O}_{V,\mu\nu}^{26} = k_{2\mu}\gamma_{\nu} \\ \mathcal{O}_{V,\mu\nu}^{27} = k_{1\nu}\gamma_{\mu} \\ \mathcal{O}_{V,\mu\nu}^{28} = k_{2\nu}\gamma_{\mu} \\ \mathcal{O}_{V,\mu\nu}^{29} = p_{1\mu}\gamma_{\nu}\not{k}_{1} \\ \mathcal{O}_{V,\mu\nu}^{30} = p_{1\nu}\gamma_{\mu}\not{k}_{1} \\ \mathcal{O}_{V,\mu\nu}^{31} = k_{1\mu}\gamma_{\nu}\not{k}_{1} \\ \mathcal{O}_{V,\mu\nu}^{32} = k_{2\nu}\gamma_{\mu}\not{k}_{1} \\ \mathcal{O}_{V,\mu\nu}^{33} = k_{2\mu}\gamma_{\nu}\not{k}_{1} \\ \mathcal{O}_{V,\mu\nu}^{33} = k_{2\mu}\gamma_{\nu}\not{k}_{1} \\ \mathcal{O}_{V,\mu\nu}^{34} = k_{1\nu}\gamma_{\mu}\not{k}_{1} \end{array}$$

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Hadronic amplitude



Diagram (a)

$$\begin{split} \mathcal{H}_{ij,ab}^{\mu\nu} &= f_{lja}(\mathbf{i}D\,d_{ilb} - F\,f_{ilb}) \times \frac{\mathbf{i}}{8} \int \frac{\mathrm{d}k^d}{(2\pi)^d} \frac{\gamma^{\nu}(k^2 + m_l \not{k} + \not{p}_1 \not{k}) \gamma_5 k^{\mu}}{[k^2 - M_b^2][(k + p_1)^2 - m_l^2][(k + k_1)^2 - m_{\beta\beta}^2]} \\ &+ (\mathbf{i}D^2\,d_{ilb}d_{lja} - D\,F\,d_{ilb}f_{lja} - D\,F\,f_{ilb}d_{lja} - \mathbf{i}F^2\,f_{ilb}f_{lja}) \times (-\frac{\mathbf{i}}{8}) \\ &\int \frac{\mathrm{d}k^d}{(2\pi)^d} \frac{\gamma^{\nu}\gamma_5(k^2 + m_l \not{k} + \not{p}_1 \not{k}) k^{\mu}}{[k^2 - M_b^2][(k + p_1)^2 - m_l^2][(k + k_1)^2 - m_{\beta\beta}^2]} \end{split}$$

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Decay width

Casimir's trick

$$\overline{|\mathcal{M}^2|} = \frac{|T_{\mathsf{lept}}|^2}{2} \operatorname{Tr}[\Gamma_1(\not\!\!\!k_1 - m_e)\bar{\Gamma}_2(\not\!\!\!k_2 + m_e)] \operatorname{Tr}[\Gamma^3(\not\!\!\!p_1 + m_\Sigma)\bar{\Gamma}^4(\not\!\!\!p_2 + m_p)]$$

$$\gamma^{\mu}\gamma^{\nu}C = \Gamma_1$$
$$\gamma^{\alpha}\gamma^{\beta}C = \Gamma_2$$

$$\sum_{i=1}^{34} (\mathcal{H}_i \mathcal{O}^i_{\mu\nu} + \mathcal{H}^A_i \mathcal{O}^{Ai}_{\mu\nu}) = \Gamma^3$$
$$\sum_{j=1}^{34} (\mathcal{H}_j \mathcal{O}^j_{\alpha\beta} + \mathcal{H}^A_j \mathcal{O}^{Aj}_{\alpha\beta}) = \Gamma^4$$

Decay width

$$\Gamma = \frac{1}{(2\pi)^3} \frac{1}{32M^3} \int_{u_{min}}^{u_{max}} \int_{4m_e^2}^{(M-m_p)^2} |\mathcal{M}|^2 ds du$$

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Dalitz plot



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Neutrinoless double beta decay in ChPT

III.Summary and Outlook

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Summary and Outlook

Summary

- The prediction of the decay amplitude of $\Sigma^- \to p e^- e^-$ can be obtained based on chiral pertubation theory
- Counter terms still need to be constructed for renormalization with EOMS scheme

Outlook

- We will extend the study to the SU(3) particles with spin- $\frac{3}{2}$ with ChPT
- We are currently using a dimension-5 operator for $\Delta L = 2$, and as the next step will calculate the decay width in the presence of dimension-7 operators

Thank you very much for your patience!