Neutrinoless double beta decay of hyperons in covariant chiral perturbation theory

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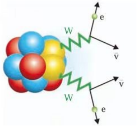
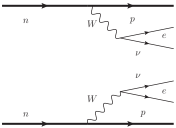
Contents

Nuclear double beta decays

- $2\nu2\beta$-decay

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





$$T_{\frac{1}{2}} \sim 10^{18-24} yr$$

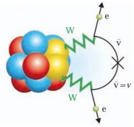
✓Experimentally Observed

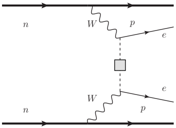
[A.s.Barabash,Phys.Rev.C81,035501(2010)]

$$^A_Z X \to {}_{Z+2}^{\;\;A} Y + 2e^- + 2\bar{\nu}_e$$

- $0\nu2\beta$-decay

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





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

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

[KamLAND-Zen Collaboration,arXiv:2406.11438 [hep-ex] (2024)]

$$^A_Z X \to {}_{Z+2}^{\;\;A} Y + 2e^-$$

Half-life of $0\nu\beta\beta$

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.

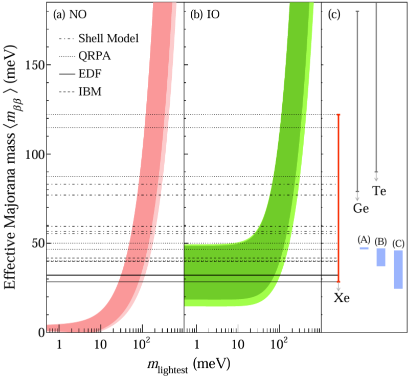
$$(T^{0\nu}_{\frac{1}{2}})^{-1} = G^{0\nu}|M^{0\nu}|^2|m_{\beta\beta}|^2$$

(Light Majorana neutrino exchange mechanism)

NMEs:

$$M^{0\nu} = \langle\Psi_f|\hat{O}^{0\nu}|\Psi_i\rangle$$

- Depending on decay operator $\hat{O}^{0\nu}$
- Differences between different nuclear models for $\Psi_{f,i}$ $\Rightarrow$Sizable uncertainties



Theoretical

Due to the lepton number violation(LNV) in the neutrinoless double beta decay process, there must be new physics to the process that goes beyond the Standard Model.

- Top-down approach: Study signals in explicit BSM
- Bottom-up approach: Work with effective field theories(EFT)

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{C_i^{(5)}}{\Lambda}\mathcal{O}_i^{(5)} + \sum_j \frac{C_j^{(6)}}{\Lambda^2}\mathcal{O}_j^{(6)} + \sum_k \frac{C_k^{(7)}}{\Lambda^3}\mathcal{O}_k^{(7)} + \sum_j \frac{C_j^{(8)}}{\Lambda^4}\mathcal{O}_j^{(8)} + \sum_j \frac{C_j^{(9)}}{\Lambda^5}\mathcal{O}_j^{(9)} + \cdots$$

$$\mathcal{O}^{(5)} = \epsilon_{kl}\epsilon_{mn}(L_k^T \mathcal{C}^{(5)} C L_m) H_l H_n$$

[Phys. Rev. Lett. 43 (1979) 1566]
[JHEP 11(2016)043]

$$\psi^2 H^4 : \quad \epsilon_{ij}\epsilon_{mn}(L_i^T C L_m) H_j H_n (H^\dagger H)$$

$$\psi^2 H^2 D^2 : \epsilon_{ij}\epsilon_{mn}(L_i^T C D_\mu L_j) H_m (D^\mu H)_n$$

$$\epsilon_{im}\epsilon_{jn}(L_i^T C D_\mu L_j) H_m (D^\mu H)_n$$

$$\psi^2 H^3 D : \quad \epsilon_{ij}\epsilon_{mn}(L_i^T C \gamma^\mu e) H_m (D_\mu H)_n$$

$$\psi^2 H^2 X : \quad \epsilon_{ij}\epsilon_{mn} g' (L_i^T C \sigma^{\mu\nu} L_m) H_j H_n B_{\mu\nu}$$

$$\epsilon_{ij}(\epsilon\tau^I)_{mn} g (L_i^T C \sigma^{\mu\nu} L_m) H_j H_n W^I_{\mu\nu}$$

$$\psi^4 D : \quad \epsilon_{ij}(\bar{d}\gamma_\mu u)(L_i^T C D^\mu L_j)$$

$$\psi^4 H : \quad \epsilon_{ij}\epsilon_{mn}(\bar{e} L_i)(L_j^T C L_m) H_n$$

$$\epsilon_{ij}\epsilon_{mn}(\bar{d}_L Q_i^T C L_m) H_n$$

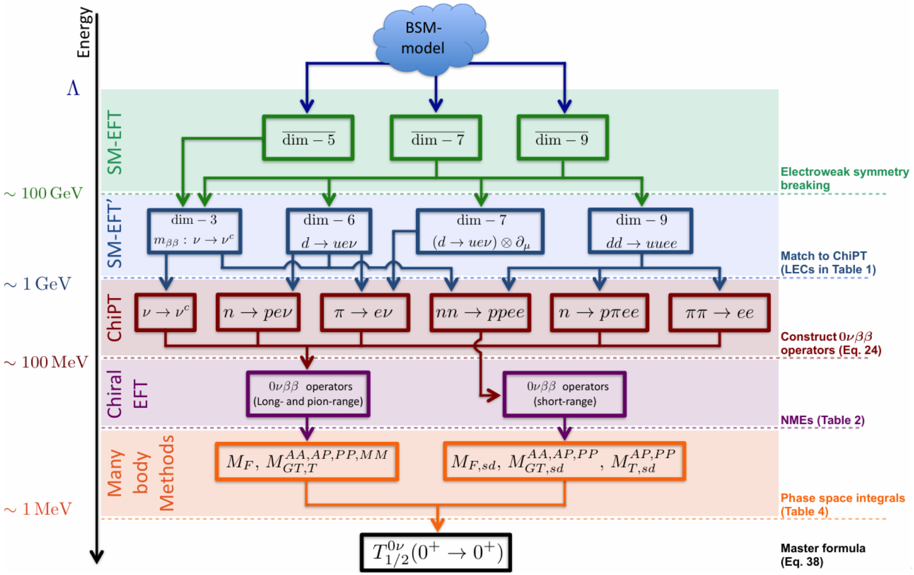
$$\epsilon_{ij}\epsilon_{mn}(\bar{d}_L Q_j^T C L_m) H_n$$

$$\epsilon_{ij}(\bar{u}_L Q_m^T C L_i) H_j$$

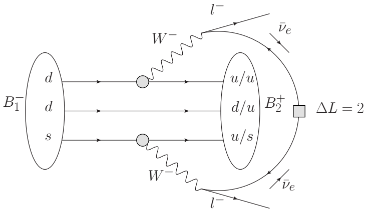
$$\epsilon_{ij}(\bar{e}\bar{d}_R)(Q_j^T C u_R) H_i$$

EFT at various energy scales

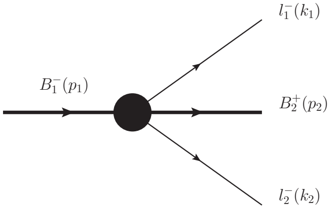
[Cirigliano,et al.JHEP12(2018)]



- 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



Quark level

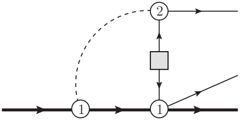


Hadron level

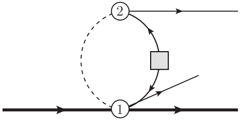
- $\Delta S = 0$: $\Sigma^-[dds] \to \Sigma^+[uus]e^-e^-$;
- $\Delta S = 1$: $\Sigma^-[dds] \to p[duu]\ell^-\ell^-$,$\Xi^-[dss] \to \Sigma^+[uus]e^-e^-$;
- $\Delta S = 2$: $\Xi^-[dss] \to p[duu]\ell^-\ell^-$.

Hyperon $0\nu2\beta$ decay in BChPT

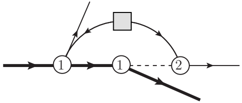
- Description of $0\nu2\beta$ decay of hyperons at one-loop level in ChPT



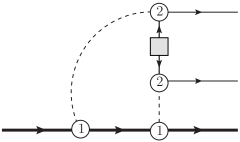
(a)



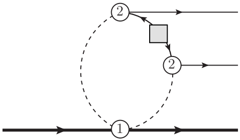
(b)



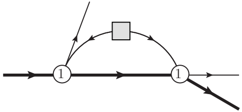
(c)



(d)



(e)



(f)

Chiral effective Lagrangian

The chiral effective Lagrangian relevant to the decay process:

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

- The LO baryon-meson interaction Lagrangian is given by

$$\mathcal{L}^{(1)}_{\rm MB} = \mathrm{Tr}\left[\bar{B}\left(i\not{D} - m\right)B\right] - \frac{D}{2}\left\langle \bar{B}\gamma^{\mu}\gamma_5\left\{u_{\mu}, B\right\}\right\rangle - \frac{F}{2}\left\langle \bar{B}\gamma^{\mu}\gamma_5\left[u_{\mu}, B\right]\right\rangle$$

- The LO chiral Lagrangian for purely mesonic interaction reads

$$\mathcal{L}^{(2)}_{M} = \frac{F_0^2}{4}\mathrm{Tr}[(D_{\mu}U)^{\dagger}D^{\mu}U] + \frac{F_0^2}{4}\mathrm{Tr}[U^{\dagger}\chi + U\chi^{\dagger}]$$

- Low-energy dimension-5 operator for the $\Delta L{=}2$ Lagrangian

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

Building block

- 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:

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

- Left-handed current:

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

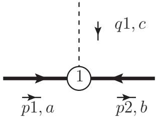
- Right-handed current:

$$r_\mu = 0$$

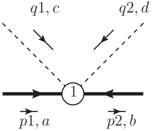
$$T_+ = \begin{pmatrix} 0 & V_{ud} & V_{us} \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} = \frac{V_{ud}}{2}(\lambda_1 + i\lambda_2) + \frac{V_{us}}{2}(\lambda_4 + i\lambda_5)$$

Feynman Rules

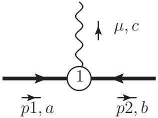
Due to the presence of the λ matrices in the Lagrangian, we can express the vertex rules as a product of the Gell-Mann part and the Dirac part



$$=\frac{1}{F_0}(Dd_{abc} + iFf_{abc})\not{q}_1 \cdot \gamma_5$$



$$=\frac{i}{2F_0^2} f_{abe} f_{cde} (\not{q}_1 - \not{q}_2)$$



$$=\frac{1}{2}\{-\gamma^{\mu} f_{abc} + \gamma^{\mu}\gamma_5(iDd_{abc} - Ff_{abc})\}$$

Amplitude structure

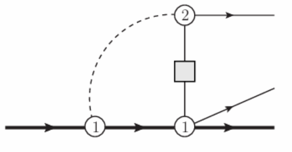
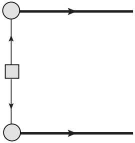


Diagram (a)



leptonic part

$$\mathcal{M} = L^{\mu\nu} H_{\mu\nu} = \underbrace{T_{\text{lept}}[\bar{u}_{eL}(k_2)\gamma^{\mu}\gamma^{\nu}C\bar{u}_{eL}^{T}(k_1)]}_{\text{leptonic}} \underbrace{H_{\mu\nu}}_{\text{hadronic}}$$

	$\Delta S = 0$	$\Delta S = 1$	$\Delta S = 2$
Process	$\Sigma^- \to \Sigma^+ e^- e^-$	$\Sigma^- \to p\ell^-\ell^-$	$\Xi^- \to p\ell^-\ell^-$
		$\Xi^- \to \Sigma^+ e^- e^-$	
T_{lept}	$8m_{\beta\beta}G_F^2V_{ud}^2$	$8m_{\beta\beta}G_F^2V_{ud}V_{us}$	$8m_{\beta\beta}G_F^2V_{us}^2$

Lorentz decomposition of hadronic tensor

$$H_{\mu\nu} = \bar{u}(p_2)\left\{\sum_{i=1}^{34}(V_i(s,u)\mathcal{O}^i_{V,\mu\nu} + A_i(s,u)\mathcal{O}^i_{A,\mu\nu})\right\}u(p_1)$$

$\mathcal{O}^1_{V,\mu\nu} = g_{\mu\nu}$
$\mathcal{O}^2_{V,\mu\nu} = \not{k}_1 g_{\mu\nu}$
$\mathcal{O}^3_{V,\mu\nu} = \gamma_\mu\gamma_\nu\not{k}_1$
$\mathcal{O}^4_{V,\mu\nu} = \gamma_\mu\gamma_\nu$
$\mathcal{O}^5_{V,\mu\nu} = k_{1\mu}k_{2\nu}$
$\mathcal{O}^6_{V,\mu\nu} = k_{1\nu}k_{2\mu}$
$\mathcal{O}^7_{V,\mu\nu} = k_{1\mu}k_{1\nu}$
$\mathcal{O}^8_{V,\mu\nu} = k_{2\mu}k_{2\nu}$
$\mathcal{O}^9_{V,\mu\nu} = p_{1\mu}k_{2\nu}$
$\mathcal{O}^{10}_{V,\mu\nu} = k_{1\nu}p_{1\mu}$
$\mathcal{O}^{11}_{V,\mu\nu} = p_{1\mu}k_{2\nu}$
$\mathcal{O}^{12}_{V,\mu\nu} = k_{1\mu}p_{1\nu}$

$\mathcal{O}^{13}_{V,\mu\nu} = p_{1\nu}k_{2\mu}$
$\mathcal{O}^{14}_{V,\mu\nu} = k_{1\mu}k_{2\nu}\not{k}_1$
$\mathcal{O}^{15}_{V,\mu\nu} = k_{1\nu}k_{2\mu}\not{k}_1$
$\mathcal{O}^{16}_{V,\mu\nu} = k_{1\mu}k_{1\nu}\not{k}_1$
$\mathcal{O}^{17}_{V,\mu\nu} = k_{2\mu}k_{2\nu}\not{k}_1$
$\mathcal{O}^{18}_{V,\mu\nu} = p_{1\mu}p_{1\nu}\not{k}_1$
$\mathcal{O}^{19}_{V,\mu\nu} = k_{1\nu}p_{1\mu}\not{k}_1$
$\mathcal{O}^{20}_{V,\mu\nu} = p_{1\mu}k_{2\nu}\not{k}_1$
$\mathcal{O}^{21}_{V,\mu\nu} = k_{1\mu}p_{1\nu}\not{k}_1$
$\mathcal{O}^{22}_{V,\mu\nu} = p_{1\nu}k_{2\mu}\not{k}_1$
$\mathcal{O}^{23}_{V,\mu\nu} = p_{1\mu}\gamma_\nu$

$\mathcal{O}^{24}_{V,\mu\nu} = p_{1\nu}\gamma_\mu$
$\mathcal{O}^{25}_{V,\mu\nu} = k_{1\mu}\gamma_\nu$
$\mathcal{O}^{26}_{V,\mu\nu} = k_{2\mu}\gamma_\nu$
$\mathcal{O}^{27}_{V,\mu\nu} = k_{1\nu}\gamma_\mu$
$\mathcal{O}^{28}_{V,\mu\nu} = k_{2\nu}\gamma_\mu$
$\mathcal{O}^{29}_{V,\mu\nu} = p_{1\mu}\gamma_\nu\not{k}_1$
$\mathcal{O}^{30}_{V,\mu\nu} = p_{1\nu}\gamma_\mu\not{k}_1$
$\mathcal{O}^{31}_{V,\mu\nu} = k_{1\mu}\gamma_\nu\not{k}_1$
$\mathcal{O}^{32}_{V,\mu\nu} = k_{2\nu}\gamma_\mu\not{k}_1$
$\mathcal{O}^{33}_{V,\mu\nu} = k_{2\mu}\gamma_\nu\not{k}_1$
$\mathcal{O}^{34}_{V,\mu\nu} = k_{1\nu}\gamma_\mu\not{k}_1$

Decay width

$$\overline{|\mathcal{M}^2|} = |T_{\textsf{lept}}|^2 \mathrm{Tr}[\Gamma_1(\not{k}_2 - m_l)\bar{\Gamma}_2(\not{k}_1 + m_l)]\mathrm{Tr}[\Gamma^3(\not{p}_1 + m_{B_1})\bar{\Gamma}^4(\not{p}_2 + m_{B_2})]$$

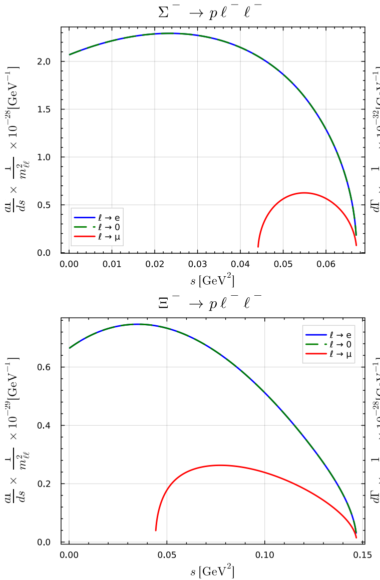
$$\gamma^\mu\gamma^\nu = \Gamma_1 \qquad \sum_{i=1}^{34}(\mathcal{H}_i\mathcal{O}^i_{\mu\nu} + \mathcal{H}^A_i\mathcal{O}^{Ai}_{\mu\nu}) = \Gamma^3$$

$$\gamma^\alpha\gamma^\beta = \Gamma_2 \qquad \sum_{j=1}^{34}(\mathcal{H}_j\mathcal{O}^j_{\alpha\beta} + \mathcal{H}^A_j\mathcal{O}^{Aj}_{\alpha\beta}) = \Gamma^4$$

Decay width

$$\Gamma = \frac{1}{(2\pi)^3}\frac{1}{32M^3}\int_{u_{min}}^{u_{max}}\int_{4m_l^2}^{(m_{B_1}-m_{B_2})^2}\overline{|\mathcal{M}|^2}dsdu$$

Differential Decay Rate



Branching Ratios

	$\Gamma_{0\nu}/\langle m_{\ell\ell}\rangle^2$ [sec^{-1}/MeV^2]	$\mathcal{B}(B_1 \to B_2\ell^-\ell^-)$
$\Sigma^- \to pe^-e^-$	1.997×10^{-5}	2.95×10^{-25}
$\Sigma^- \to \Sigma^+e^-e^-$	3.068×10^{-12}	4.54×10^{-32}
$\Sigma^- \to p\mu^-\mu^-$	1.723×10^{-6}	2.81×10^{-12}
$\Xi^- \to \Sigma^+e^-e^-$	8.741×10^{-6}	1.43×10^{-25}
$\Xi^- \to pe^-e^-$	1.263×10^{-6}	2.07×10^{-26}
$\Xi^- \to p\mu^-\mu^-$	3.128×10^{-7}	5.65×10^{-13}

Decay rates (normalized to the effective neutrino mass $\langle m_{\ell\ell}\rangle^2$) and branching ratios for $\Delta L = 2$ hyperon decays. We use $\langle m_{ee}\rangle^2 = (10\,\text{eV})^2$ and $\langle m_{\mu\mu}\rangle^2 = (105\,\text{MeV})^2$ to evaluate the branching ratios.

Comparison

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

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

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

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

[L.F Li Phys.Rev.D76, 116008 (2007)]

3. Based on the MIT bag model: [L.F Li Phys.Rev.D87,036010 (2013)]

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

Advantage:

- Nuclear $0\nu2\beta$ decays $\Delta S = 0$; Hyperon $0\nu2\beta$ decays $\Delta S \neq 0$.
- Hyperon factory @ BESIII & STCF: $J/\Psi \to \Sigma\bar{\Sigma}$.

Summary and Outlook

Summary

- The amplitude of neutrinoless double beta decay involving spin-1/2 hyperons, such as $\Sigma^- \to p\ell^-\ell^-$, can be predicted using 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!