Study of Non Standard Interactions in Rare Decays of Hyperons with Missing Energy

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Abstract

We study rare decays of hyperons involving di-neutrinos in the final state \( \Lambda \rightarrow n\bar{\nu}, \Sigma^+ \rightarrow \rho\bar{\nu}, \Xi^0 \rightarrow \Delta\bar{\nu}, \Xi^0 \rightarrow \Sigma^0\bar{\nu}, \Xi^- \rightarrow \Sigma^-\bar{\nu}, \Omega^- \rightarrow \Xi^-\bar{\nu} \) in the standard model and compare them with other models. It is claimed that the branching ratio calculated in this article are 2 times the values of 331 model and exceptionally large than the previously calculated values. We explore the nonstandard neutrino interactions (NSI) and constrain NSIs free parameter \( \epsilon^{\mu\beta}_{\nu} \) with these decays. We obtain stringent bounds on \( \epsilon^{\mu\beta}_{\nu} \) (\( \beta = e, \mu \)) of \( O(10^{-2}) \). We show that branching ratios (\( Br \)) could be in the range of BESIII, if constraints are \( O(0.3) \).

Keywords: NSIs, Rare Decays, FCNC, Hyperons Decays, BSM

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1 Introduction

Standard Model (SM) predictions have been verified experimentally to the highest level of precision [1]. But, along with theoretical inconsistency, it lacks any explanation for a possible pattern for particles mass. The experiments on B meson [2] are also giving some cracks in standard model. We need New Physics (NP) to explain dark matter and matter anti-matter asymmetry. Gravity is not included in the SM. Theoretically SM has limitations and there can be some new particles as well as new interactions. It has been believed that standard model is a low energy approximation of more general theory. So, many theoretical extensions of standard model (SM) has been presented. But, so far, the only concrete evidence against SM has been provided by the neutrino oscillations [3, 4]. To explore NP the study of mesonic rare decays involving neutrinos in final state two processes \( K^+ \rightarrow \pi^+\bar{\nu} \) and \( K_L^0 \rightarrow \pi^0\bar{\nu} \) has been used due to their theoretical cleanness. This decays occur through flavor changing neutral currents (FCNC) which are highly suppressed [5] in SM at tree level due to GIM mechanism [6].
They occur at loop diagram [7], so their contributions are very small. The discrepancies between experiments and theory (SM) for such reactions provide us an excellent window towards New Physics. New particles can be added in the loops to improve the theory. So, FCNC reactions involving neutrinos in the final state can be interesting. For the case of $K^+ \to \pi^+ \bar{\nu}_\mu$, there is a very small difference between theory and experiment. The effects of Nonstandard Interactions in in rare decays of mesons has been studied in [8, 9, 10, 11, 12, 13, 14, 15]. Similar to this mesonic rare decay we have hyperons rare decays ($\Lambda \to n\bar{\nu}_\mu$, $\Sigma^+ \to p\bar{\nu}_\mu$, $\Xi^0 \to \Lambda\bar{\nu}_\mu$, $\Xi^0 \to \Sigma^0\bar{\nu}_\mu$, $\Xi^- \to \Sigma^-\bar{\nu}_\mu$ and $\Omega^- \to \Xi^-\bar{\nu}_\mu$) accessible to BESIII. These decays can be written as

$$B_{\text{initial}} \to B_{\text{final}} \bar{\nu}_\alpha \nu_\beta$$

where mass of $B_{\text{initial}} >$ mass of $B_{\text{final}}$ and both are pseudoscalar mesons.

At the quark level all these reactions are represented by the equation $s \to d\bar{\nu}_\alpha \nu_\beta$

where $s$ and $d$ are representing strange and down quarks having.

$\alpha = \beta$, allowed in SM, effective Lagrangian can be written as:

$$L_{\text{eff}}^{\text{SM}} = -2\sqrt{2}G_F (\bar{\nu}_\alpha \gamma^\mu L \nu_\alpha)(\bar{f} \gamma^\mu P f)$$

where $\alpha$ corresponds to the light neutrino flavor, $f$ denote a charged lepton or quark, where we are only dealing with quarks and $P = R$ or $L$ with $R(L) = (\frac{1 + \gamma_5}{2})$.

$\alpha \neq \beta$; is strictly forbidden in SM, only possible in new physics scenario for which we are using Non standard interactions (NSI).

In the study of rare decays we use Effective Hamiltonian (EH) which is a low energy approximation of the whole theory. EH is obtained by the use of operator product expansion (OPE) and renormalization group (RG). By this approach we can easily separate short-distance contributions from long distance contributions and study them within perturbation QCD. The long distance contributions are carried by matrix elements of the operators. These matrix elements require non-perturbative methods for their calculation and so they are model dependent. $s \to d\nu\bar{\nu}$ is a short distance dominated process and its hadronic part can be extracted by using a tree level process, making it a clean process.

NP can be searched in two ways (a) Model independent way and (b) Model Dependent way e.g.; left right symmetric model, 331 model, SUSY etc. We study the decays $s \to d\nu\bar{\nu}$ to find out the contribution from the new physics. We concentrate only on $\Lambda \to n\bar{\nu}_\mu$, $\Sigma^+ \to p\bar{\nu}_\mu$, $\Xi^0 \to \Lambda\bar{\nu}_\mu$, $\Xi^0 \to \Sigma^0\bar{\nu}_\mu$, $\Xi^- \to \Sigma^-\bar{\nu}_\mu$, $\Omega^- \to \Xi^-\bar{\nu}_\mu$.

2 Experimental Prospects

These processes are yet to detect in the experiments but Beijing Electron Spectrometer (BESIII) is proposed to observe $J/\Psi$ decay into hyperon pairs. It is
estimated that about $10^6$ to $10^{10}$ hyperons will be produced. This would be an excellent opportunity to observe $\Lambda$, $\Sigma$, $\Xi$ and $\Omega$. This experiment is capable of observing Branching ratios of $10^{-5}$ to $10^{-8}$ of these decays. The expected results are published in [30] and listed in table 1.

3 Theory

The effective Lagrangian for such interactions in model independent way is given in [16] and can be written as

$$L^{\text{eff}}_{\text{NSI}} = -2\sqrt{2} G_F \left[ \sum_{\alpha=\beta} \epsilon^{\text{NP}}_{\alpha\beta} (\bar{\nu}_\alpha \gamma_\mu \nu_\beta)(\bar{f} \gamma^\mu P f) + \sum_{\alpha \neq \beta} \epsilon^{\text{NP}}_{\alpha\beta} (\bar{\nu}_\alpha \gamma_\mu \nu_\beta)(\bar{f} \gamma^\mu P f) \right]$$

(1)

Here $\epsilon^{\text{NP}}_{\alpha\beta}$ is the parameter for NSIs, which carries information about dynamics. NSIs are thought to be well-matched with the oscillation effects along with new features in neutrino searches [17, 18, 19, 20, 21]. Expected constraints for first two generations of leptons $\epsilon^{\text{NP}}_{\nu_l}$ ($l = e, \mu$) by tree level processes are at $O(10^{-3})$ by future $\sin^2(\theta)$ experiments [22]. For third generation ($\tau$) we need decays which occur at loop level, whose current limit is $O(1)$. The limit of $O(0.3)$ is expected for for third generation ($\tau$) KamLAND data [23] and solar neutrino data [24, 25].

The Standard Model interactions are shown by the similar diagrams as shown in figure 1. The effective Hamiltonian is shown of the process $\pi \rightarrow d \tau v$ in SM and NSIs is given by equations 2 and 3 respectively.

$$H^{\text{SM}}_{\text{eff}} = \frac{G_F}{\sqrt{2}} \frac{\alpha_{\text{em}}}{2 \pi \sin^2 \theta} \sum_{\alpha=\beta=e,\mu,\tau} \left( V^{\text{ud}}_{\alpha \beta} X^{\text{L}}_{\alpha \beta} + V^{\text{td}}_{\alpha \beta} X_{\alpha \beta} \right) \times (\bar{d} \tau v)^{-A} (\nu_\alpha \bar{v}_\beta)^{-A}$$

(2)

where $X^{\text{L}}_{\alpha \beta}$ is the charm quark contribution. In this case NSI becomes

$$H^{\text{NSI}}_{\text{eff}} = \frac{G_F}{\sqrt{2}} \left( V^{\text{ud}}_{\alpha \beta} V_{\text{ad}} \frac{\alpha_{\text{em}}}{4 \pi \sin^2 \theta} \alpha_{\text{L}} \ln \frac{\Lambda}{m_W} \right) \times (\bar{d} \tau v)^{-A} (\nu_\alpha \bar{v}_\beta)^{-A}$$

(3)

4 Branching Ratios of Decays in SM and NSIs

We get the branching ratios for such reactions by normalizing with a tree level process which are by isospin symmetry which will reduce hadronic uncertainties. Factor of three is due to summation over three flavours of neutrinos.

$$\frac{\text{Br}(\Lambda \rightarrow \mu e \pi^- \pi^0)}{\text{Br}(\Lambda \rightarrow \mu e \pi^0 \gamma)} = \frac{3 \alpha_{\text{em}} \Gamma_{\text{ee}}}{3 \alpha_{\text{em}} \Gamma_{\text{mu}} \sin^2 \theta_w} \left( \frac{\left( \text{Im} \lambda^\mu X(x_t) \right)^2 + \left( \text{Re} \lambda^\mu + \frac{\text{Re} \lambda^\mu}{\Lambda} \right) (\text{Re} P_e (X) + \text{Re} P_e) \right)^2}{\left( \text{Im} \lambda^e X(x_t) \right)^2 + \left( \frac{\text{Re} \lambda^e + \frac{\text{Re} \lambda^e}{\Lambda} \right) (\text{Re} P_e (X) + \text{Re} P_e) \right)^2}$$

$$\frac{\text{Br}(\Sigma^+ \rightarrow \mu^+ e^- \pi^-)}{\text{Br}(\Sigma^+ \rightarrow \mu^+ e^- \pi^0)} = \frac{3 \alpha_{\text{em}} \Gamma_{\text{ee}}}{3 \alpha_{\text{em}} \Gamma_{\text{mu}} \sin^2 \theta_w} \left( \frac{\left( \text{Im} \lambda^\mu X(x_t) \right)^2 + \left( \text{Re} \lambda^\mu + \frac{\text{Re} \lambda^\mu}{\Lambda} \right) (\text{Re} P_e (X) + \text{Re} P_e) \right)^2}{\left( \text{Im} \lambda^e X(x_t) \right)^2 + \left( \frac{\text{Re} \lambda^e + \frac{\text{Re} \lambda^e}{\Lambda} \right) (\text{Re} P_e (X) + \text{Re} P_e) \right)^2}$$

$$\frac{\text{Br}(\Xi^- \rightarrow \mu^- e^+ \pi^+)}{\text{Br}(\Xi^- \rightarrow \mu^- e^+ \pi^0)} = \frac{3 \alpha_{\text{em}} \Gamma_{\text{ee}}}{3 \alpha_{\text{em}} \Gamma_{\text{mu}} \sin^2 \theta_w} \left( \frac{\left( \text{Im} \lambda^\mu X(x_t) \right)^2 + \left( \text{Re} \lambda^\mu + \frac{\text{Re} \lambda^\mu}{\Lambda} \right) (\text{Re} P_e (X) + \text{Re} P_e) \right)^2}{\left( \text{Im} \lambda^e X(x_t) \right)^2 + \left( \frac{\text{Re} \lambda^e + \frac{\text{Re} \lambda^e}{\Lambda} \right) (\text{Re} P_e (X) + \text{Re} P_e) \right)^2}$$

$$\frac{\text{Br}(\Xi^- \rightarrow \mu^- e^+ \pi^0)}{\text{Br}(\Xi^- \rightarrow \mu^- e^+ \pi^0)} = \frac{3 \alpha_{\text{em}} \Gamma_{\text{ee}}}{3 \alpha_{\text{em}} \Gamma_{\text{mu}} \sin^2 \theta_w} \left( \frac{\left( \text{Im} \lambda^\mu X(x_t) \right)^2 + \left( \text{Re} \lambda^\mu + \frac{\text{Re} \lambda^\mu}{\Lambda} \right) (\text{Re} P_e (X) + \text{Re} P_e) \right)^2}{\left( \text{Im} \lambda^e X(x_t) \right)^2 + \left( \frac{\text{Re} \lambda^e + \frac{\text{Re} \lambda^e}{\Lambda} \right) (\text{Re} P_e (X) + \text{Re} P_e) \right)^2}$$
Branching ratios VS hyperons. whose chances are more in normal mass hierarchy of neutrinos due to decays of normal neutrinos. Branching ratios of the tree level processes are given in table 5. The plots of this Br and new physics parameter are at different values of new parameter. Br = 0.901 and \( \frac{\Delta m^2_{31}}{\Delta m^2_{21}} \) given and calculated in [26] for \( \nu^+ \rightarrow \pi^+ \nu \). This factor will remain same for hyperons decays. 

\[
\text{Re} \lambda = 0 \quad c; u \\
\text{Im} \lambda = 0 \quad c; u
\]

As in CPT, \( \lambda_c = -\lambda \). Similarly for all others can be found. If we take the treatment similar to \( \nu^+ \rightarrow \pi^+ \nu \), then experimental and theoretical values will be very close, and we find following stringent bounds on nonstandard parameter.

\[
\text{Br}(\Delta \rightarrow \nu \nu)_{SM} - \text{Br}(\Delta \rightarrow \nu \nu)_{\text{experimental}} = O(10^{-12})
\]

\( \alpha_{\beta} \leq 0.014 \) \( \ln \frac{m_W}{m_{\nu}} \).

Similarly for all others can be found.

\[
\text{Br}(\gamma \rightarrow \Delta)_{SM} = \frac{\alpha^2_{\text{eM}}}{{V^{*}_{us}}^2 |V_{ud}|} \frac{1}{2} \frac{e_{\alpha \beta}^{uL}}{
u_{\nu}} \ln \frac{\Delta m_{\nu}}{m_{\nu}} \left| 2 \text{Br}(\gamma \rightarrow \Delta)_{\text{exp}} \right|
\]

\( \alpha_{\beta} \leq 0.009 \) \( \ln \frac{m_W}{m_{\nu}} \).

\[
\text{Br}(\Xi \rightarrow \Delta \nu)_{SM} = \frac{\alpha^2_{\text{eM}}}{{V^{*}_{us}}^2 |V_{ud}|} \frac{1}{2} \frac{e_{\alpha \beta}^{uL}}{
u_{\nu}} \ln \frac{\Delta m_{\nu}}{m_{\nu}} \left| 2 \text{Br}(\Xi \rightarrow \Delta \nu)_{\text{exp}} \right|
\]

\( \alpha_{\beta} \leq 0.012 \) \( \ln \frac{m_W}{m_{\nu}} \).

\[
\text{Br}(\Xi \rightarrow \Sigma \nu)_{SM} = \frac{\alpha^2_{\text{eM}}}{{V^{*}_{us}}^2 |V_{ud}|} \frac{1}{2} \frac{e_{\alpha \beta}^{uL}}{
u_{\nu}} \ln \frac{\Delta m_{\nu}}{m_{\nu}} \left| 2 \text{Br}(\Xi \rightarrow \Sigma \nu)_{\text{exp}} \right|
\]

\( \alpha_{\beta} \leq 0.018 \) \( \ln \frac{m_W}{m_{\nu}} \).

\[
\text{Br}(\Xi \rightarrow \Sigma \nu)_{SM} = \frac{\alpha^2_{\text{eM}}}{{V^{*}_{us}}^2 |V_{ud}|} \frac{1}{2} \frac{e_{\alpha \beta}^{uL}}{
u_{\nu}} \ln \frac{\Delta m_{\nu}}{m_{\nu}} \left| 2 \text{Br}(\Xi \rightarrow \Sigma \nu)_{\text{exp}} \right|
\]

\( \alpha_{\beta} \leq 0.019 \) \( \ln \frac{m_W}{m_{\nu}} \).

\[
\text{Br}(\Xi \rightarrow \Xi \nu)_{SM} = \frac{\alpha^2_{\text{eM}}}{{V^{*}_{us}}^2 |V_{ud}|} \frac{1}{2} \frac{e_{\alpha \beta}^{uL}}{
u_{\nu}} \ln \frac{\Delta m_{\nu}}{m_{\nu}} \left| 2 \text{Br}(\Xi \rightarrow \Xi \nu)_{\text{exp}} \right|
\]

\( \alpha_{\beta} \leq 0.012 \) \( \ln \frac{m_W}{m_{\nu}} \).

As in \( e_{\alpha \beta}^{uL} \), \( \alpha \) and \( \beta \) can take any leptons, we pick out tau as one of the lepton whose chances are more in normal mass hierarchy of neutrinos due to decays of hyperons.

5 Branching ratios VS \( e_{\alpha \beta}^{uL} \) Plots

The plots of this Br and new physics parameter are at different values of new physics energy scale \( \Lambda \) is given figure 2 at current experimental value of \( \alpha_{\beta} O(1) \)
and in figure 3 at future expected value of $O(0.3)$.

6 Comparison of the Results and Conclusion

Standard model branching ratios calculated and listed in table 1 are two times the values of 331- model in reference [29] and $10^{-10}$ enhanced as compared to reference [28]. It is evident from the plots and table 1 and 2 that NSIs branching ratios are in the range of sensitivity of BESIII. The parameter corresponding to these branching ratios is NSIs parameter is of the order of 1 which is current experimental value and $O(0.3)$ which is future expected value. If these reactions could not be found at BESIII with these branching ratios than more stringent bounds on new physics parameter could be imposed. If the situation remains exactly the same as it is for $k^+ \rightarrow \pi^+\nu\bar{\nu}$, then the bounds on NSIs parameter are $O(10^{-2})$.

| Decay Modes | $\Lambda \rightarrow n\nu\bar{\nu}$ | $\Sigma^+ \rightarrow p\nu\bar{\nu}$ | $\Xi \rightarrow \Lambda\nu\bar{\nu}$ |
|-------------|---------------------------------|---------------------------------|---------------------------------|
| Tree level Process | $\Lambda \rightarrow p e^-\bar{\nu}_e$ | $\Sigma^- \rightarrow n e^-\bar{\nu}_e$ | $\Xi^- \rightarrow \Lambda e^-\bar{\nu}_e$ |
| Exp. values | $8.32 \times 10^{-4}$ | $1.01 \times 10^{-3}$ | $5.63 \times 10^{-4}$ |
| SM Br in this work | $1.45 \times 10^{-12}$ | $3.56 \times 10^{-12}$ | $1.97 \times 10^{-12}$ |
| SM Br in [28] | $7.1 \times 10^{-13}$ | $4.3 \times 10^{-13}$ | $6.3 \times 10^{-13}$ |
| Br in 3-3-1 model [29] | $2.91 \times 10^{-12}$ | $7.12 \times 10^{-12}$ | $3.94 \times 10^{-12}$ |
| NSIs Br | $2.5 \times 10^{-8}$ | $6 \times 10^{-8}$ | $3.5 \times 10^{-8}$ |
| Extended BESIII [30] | $< 3 \times 10^{-7}$ | $< 4 \times 10^{-7}$ | $< 8 \times 10^{-7}$ |
| $\epsilon_{\tau\tau}^{ul}$ at Current exp. Limit | 1 | 1 | 1 |

| Decay Modes | $\Xi^0 \rightarrow \Sigma^0 e^-\bar{\nu}_e$ | $\Xi^- \rightarrow \Sigma^0 e^-\bar{\nu}_e$ | $\Omega^- \rightarrow \Xi^0 e^-\bar{\nu}_e$ |
|-------------|---------------------------------|---------------------------------|---------------------------------|
| Tree level Process | $\Xi^0 \rightarrow \Sigma^+ e^-\bar{\nu}_e$ | $\Xi^- \rightarrow \Sigma^0 e^-\bar{\nu}_e$ | $\Omega^- \rightarrow \Xi^0 e^-\bar{\nu}_e$ |
| Exp. values | $2.52 \times 10^{-4}$ | $8.7 \times 10^{-3}$ | $5.6 \times 10^{-3}$ |
| SM Br in this work | $8.82 \times 10^{-13}$ | $8.11 \times 10^{-12}$ | $1.96 \times 10^{-11}$ |
| SM Br in [28] | $1 \times 10^{-13}$ | $1.3 \times 10^{-13}$ | $4.9 \times 10^{-13}$ |
| Br in 3-3-1 model [29] | $1.76 \times 10^{-12}$ | $1.62 \times 10^{-11}$ | $3.92 \times 10^{-11}$ |
| NSIs Br | $1.5 \times 10^{-8}$ | $1.5 \times 10^{-7}$ | $3.5 \times 10^{-7}$ |
| Extended BESIII [30] | $< 9 \times 10^{-7}$ | $-$ | $< 2.6 \times 10^{-7}$ |
| $\epsilon_{\tau\tau}^{ul}$ at Current exp. Limit | 1 | 1 | 1 |

Table 1: Comparison of Branching Ratios with 331-model and Previously Calculated in the Literature. Comparison for Br of NSIs and BESIII Results is provided. Nonstandard parameter is of the $O(1)$ which is Current experimental limit.
Decay Modes

| Decay Modes | $\Lambda \rightarrow n\nu\bar{p}$ | $\Sigma^+ \rightarrow p\nu\bar{p}$ | $\Xi^- \rightarrow \Lambda\nu\bar{p}$ | $\Xi^- \rightarrow \Sigma^0\nu\bar{p}$ | $\Xi^- \rightarrow \Sigma^-\nu\bar{p}$ | $\Omega^- \rightarrow \Xi^-\nu\bar{p}$ |
|-------------|--------------------------------|---------------------------------|---------------------------------|--------------------------------|--------------------------------|--------------------------------|
| NSIs Br     | $2 \times 10^{-9}$             | $8 \times 10^{-9}$              | $4 \times 10^{-9}$              | $2 \times 10^{-9}$              | $1.0 \times 10^{-8}$             | $3 \times 10^{-8}$              |
| $e_{\mu\mu}^\text{at Future Limit}$ | 0.3                           | 0.3                             | 0.3                             | 0.3                             | 0.3                             | 0.3                             |

Table 2: Br of NSIs and Nonstandard parameter is of the O(0.3) which is the Future Expected Value.

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Figure 1: Difference between Standard Model and Nonstandard Model Diagram. 
Bola is representing nonstandard interaction parameter.
Figure 2: Nonstandard Intersections Branching Ratios as a function of Nonstandard Interaction Parameter at Different values of New Physics Scale, alpha and beta are both representing tau here.
Figure 3: 3-D Plot of Nonstandard Intersections Branching Ratios as a function of Nonstandard Interaction Parameter $O(0.3)$ at Different values of New Physics Scale