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Study of an anomalous tau lepton decay using a chiral Lagrangian with vector mesons

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Abstract

The hadronic tau decay $\tau^- \to \nu_\tau \eta\pi^-\pi^0$ occurs through V-A weak current. In this decay mode, the vector current contribution is intrinsic parity violating and the axial current contribution is G parity violating. The latter contribution is suppressed due to tiny isospin breaking. We have computed both vector and axial vector form factors using a chiral Lagrangian with vector mesons including the effect of isospin breaking and intrinsic parity violation. A numerical result of the invariant mass distribution is shown and the structure of ρ resonance can be seen in the distribution with respect to $M_{\pi^-\pi^0}$.

Keywords: Chiral Lagrangian, Intrinsic Parity, G parity and Isospin, hadronic *tau* decay

1. Introduction: Intrinsic Parity violation of τ decay

Many hadronic τ decay modes are found. Among them, decay modes with more than two pseudo-Nambu Goldstone bosons as a final state are interesting since they include both intrinsic parity (IP) violating and conserving amplitudes [1],[2],[3],[4]. IP for bound state of quark and anti-quark is assigned to scalar, pseudo-scalar, vector and axial vector mesons.

$$\begin{aligned} \mathrm{IP} = +1, &\quad S_{ij} = \bar{q}_j q_i, V_{\mu ij} = \bar{q}_j \gamma_\mu q_i, \\ \mathrm{IP} = -1, &\quad P_{ij} = i\bar{q}_j \gamma_5 q_i, A_{\mu ij} = \bar{q}_j \gamma_\mu \gamma_5 q_i. \end{aligned} \tag{1}$$

With this assignment, IP is the sign which one obtains by replacing γ_5 with $-\gamma_5$. As for gauge bosons, which are not bound state of quark and anti-quark, vector gauge boson is regarded as,

$$V_\mu = \frac{A_{L\mu} + A_{R\mu}}{2}, \tag{2}$$

where A_L (A_R) denotes the gauge boson which couples to left(right)-handed quark. The IP is defined as the sign which one obtains by interchanging A_L and A_R in Eq.(2). Therefore, IP of a single photon is +1.

The hadronic current of the weak decay amplitude

	G	$e^{i\pi I_y}$	C	IP
π^+	-1	π^-	$-\pi^-$	-1
π^0	-1	$-\pi^0$	π^0	-1
π^-	-1	π^+	$-\pi^+$	-1
η_8	$+1$	η_8	η_8	-1
$\bar{d}\gamma_\mu u$	$+1$	$-\bar{u}\gamma_\mu d$	$-\bar{u}\gamma_\mu d$	$+1$
$\bar{d}\gamma_\mu\gamma_5 u$	-1	$-\bar{u}\gamma_\mu\gamma_5 d$	$\bar{u}\gamma_\mu\gamma_5 d$	-1

Table 1: Assignment of G parity and Intrinsic Parity (IP) on π,η_8 ,vector and axial vector current

for $\tau^- \to \nu_\tau \eta\pi^-\pi^0$ is written in terms of the sum of the matrix element of vector current and the matrix element of axial current. The IP of the (axial) vector current is +1(−1) and the IP of the final state; $\eta\pi^0\pi^-$ is −1. The vector current contribution corresponds to the

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intrinsic parity violating process and the axial current contribution is intrinsic parity conserving one.

Next we consider another parity called G parity. G parity is defined as $Ce^{i\pi I_y}$. As shown in Table 1, G parity for η is +1 which is different from pion's G parity. G parity and IP of vector current are the same to each other and is +1. Their assignment on axial current is also the same and it is −1. One also notes that pion's G parity and IP are the same to each other and they are −1. Therefore vector current contribution is G parity conserving and IP violating while the axial current contribution is G parity violating and IP conserving.

2. Interaction and Form factors

The weak interaction which is relevant for $\tau^- \to \nu_\tau \eta\pi^-\pi^0$ is given as,

$$-\mathcal{L}_{\rm int} = \frac{G_F}{\sqrt{2}} V_{ud}^* \bar{\nu}_\tau \gamma_\mu (1-\gamma_5)\tau \bar{d}\gamma_\mu(1-\gamma_5)u. \tag{3}$$

The hadronic matrix elements for vector and axial vector currents between vacuum and $\eta\pi^-\pi^0$ are written as,

$$\begin{aligned} \langle \eta\pi^-\pi^0|\bar{d}\gamma_\mu u|0\rangle &= -iV_{3\mu}F_3, \\ \langle \eta\pi^-\pi^0|\bar{d}\gamma_\mu\gamma_5 u|0\rangle &= V_{1\mu}F_1 \\ &+ V_{2\mu}F_2 + V_{4\mu}F_4, \end{aligned} \tag{4}$$

where F_i $(i = 1-4)$ are form factors and $V_{i\mu}$ are written in terms of the four vectors of mesons in the final states.

$$\begin{aligned} V_{1\mu} &= (p_{\pi^-} - p_\eta)_\mu - Q_\mu \frac{(p_{\pi^-} - p_\eta)\cdot Q}{Q^2}, \\ V_{2\mu} &= (p_{\pi^0} - p_\eta)_\mu - Q_\mu \frac{(p_{\pi^0} - p_\eta)\cdot Q}{Q^2}, \\ V_{3\mu} &= \epsilon_{\mu\nu\rho\sigma} p^\nu_{\pi^-} p^\rho_{\pi^0} p^\sigma_\eta, \\ V_{4\mu} &= Q_\mu \equiv (p_{\pi^0} + p_\eta + p_{\pi^-})_\mu, \end{aligned} \tag{5}$$

where $\epsilon^{0123} = 1$. The form factor F_3 for vector current is G parity conserving and IP violating. The axial vector form factors F_1, F_2, and F_4 are G parity violating and IP conserving.

3. Isospin breaking and π_0 and $\eta(\eta')$ mixing

To compute the matrix element for the hadronic current, we introduce a chiral Lagrangian with vector mesons. The axial vector form factor becomes non-zero due to the isospin violation and we must keep the mass difference of up quark and down quark. Since the IP is conserved for the matrix element for the axial current, we adopt the IP conserving part of Lagrangian [5],

$$\begin{aligned} \mathcal{L} &= \frac{f^2}{4}{\rm Tr}(D_\mu U D^\mu U^\dagger) \\ &+ B{\rm Tr}[M_q(U+U^\dagger)] \\ &- ig_{2p}{\rm Tr}(\xi M_q \xi - \xi^\dagger M_q \xi^\dagger)\cdot\eta_0 \\ &+ \frac{1}{2}\partial_\mu\eta_0\partial^\mu\eta_0 - \frac{M_0^2}{2}\eta_0^2 \\ &+ M_V^2{\rm Tr}\left[\left(V_\mu - \frac{\alpha_\mu}{g}\right)^2\right], \end{aligned} \tag{6}$$

where we use SU(3) octet mesons which are given by 3×3 matrix; $\pi = \sum_{a=1}^8 \pi^a T^a$ to write the pseudo Nambu Goldstone bosons. The fields which appear in Eq.(6) are given as,

$$\begin{aligned} \xi &= \exp(i\frac{\pi}{f}), \quad U = \xi^2, \\ D_\mu U &= (\partial_\mu + iA_{L\mu})U - iUA_{R\mu}, \\ D_\mu U^\dagger &= (\partial_\mu + iA_{R\mu})U^\dagger - iU^\dagger A_{L\mu}, \\ \alpha_\mu &= \frac{1}{2i}(\xi^\dagger D_{L\mu}\xi + \xi D_{R\mu}\xi^\dagger), \end{aligned} \tag{7}$$

where $D_{L\mu} = \partial_\mu + iA_{L\mu}$ and $D_{R\mu} = \partial_\mu + iA_{R\mu}$. V_μ denotes SU(3) vector mesons octet including ρ, K^*, and ω_8. η_0 denotes SU(3) singlet pseudo-scalar meson. The term proportional to g_{2p} leads to octet and singlet mixing such as $\pi_0 - \eta_0$ mixing and $\eta_8 - \eta_0$ mixing. The Lagrangian Eq.(6) is invariant under replacement $\pi \to -\pi, (A_L, A_R) \to (A_R, A_L)$ and it is IP conserving. We introduce isospin breaking by keeping the mass difference of up quark and down quark and the current quark mass M_q is given as,

$$M_q = \begin{pmatrix} m_u & 0 & 0 \\ 0 & m_d & 0 \\ 0 & 0 & m_s \end{pmatrix}. \tag{8}$$

π_0 and the other isosinglet mesons η, η' are mixed. Since the axial vector form factor is G parity violating and very sensitive to the mixing matrix of the neutral mesons, we investigate their mass squared matrix,

$$M^2 = \begin{pmatrix} M^2_{\pi^+} & \frac{\Delta_K}{\sqrt{3}} & -G_{2p}\Delta_K \\ \frac{\Delta_K}{\sqrt{3}} & \frac{2\Sigma_K - M^2_{\pi^+}}{3} & \frac{G_{2p}(\Sigma_K - 2M^2_{\pi^+})}{\sqrt{3}} \\ -G_{2p}\Delta_K & \frac{G_{2p}(\Sigma_K - 2M^2_{\pi^+})}{\sqrt{3}} & M_0^2 \end{pmatrix}, \tag{9}$$

where $\Delta_K = M^2_{K^+} - M^2_{K^0}, \Sigma_K = M^2_{K^+} + M^2_{K^0}$ and $G_{2p} = \frac{g_{2p}f}{B}$. We note Δ_K denotes the isospin breaking and is

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