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Mesonic decays of τ^- lepton: Effects of neutrino mass and mass mixing

R R L SHARMA* and N K SHARMA
Department of Physics, University of Rajasthan, Jaipur 302 004, India
*On leave from Government College, Dholpur 328 001, India

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Abstract. Experimentally established mesonic decays of τ^- lepton have been re-examined with the inclusion of the effects of finite neutrino mass and the associated mass mixing in the form of Kobayashi-Maskawa mixing matrix. A comparison with the experimentally predicted decay probabilities provides limits for the ν_τ mass which are finite in all decays except for the lower limit in mass mixing case of the decay $\tau^- \to K^{*-}(892) + \nu_\tau$ for which $m_{\nu_\tau} = (420 \pm 610)$ MeV. The large error in this value is because of (i) large errors in the experimental values of life time and branching ratio for this decay and (ii) the KM mixing used in the calculations. The ratio of parity-violating to parity-conserving terms in the differential decay probabilities of various decays differs slightly from their values corresponding to those with vanishing ν_τ mass.

Keywords. τ^- lepton; Kobayashi-Maskawa mixing matrix; Tau neutrino; neutrino mass; mass mixing.

1. Introduction

Massive neutrinos, their mixing and oscillations (Maki *et al* 1962; Bilenky and Pontecorvo 1978; Lyubimov and De Rujula 1981 and De Rujula and Lusignoli 1982) have become a field of immense current importance especially after the reporting of the finite electron neutrino mass by Lyubimov *et al* 1980. Effects of inclusion of these have been calculated theoretically with predictions that could be tested in experiments in the near future. In particular, processes involving β-decays (Bergkvist 1972; De Rujula and Lusignoli 1982) and muon decay (Kalyaniak and Ng 1981) have attracted maximum attention because of their obvious importance and accessibility.

In this paper we report the results of our calculations on the experimentally established mesonic decays of τ^- lepton in the lowest order. The effects of finite neutrino mass and their associated mixing are included with the use of mixing mass matrix (Kobayashi and Maskawa 1973). Bilenky and Pontecorvo (1978), and Shrock (1980) have emphasized that the effects of finite neutrino mass should be much more pronounced and detectable in two body mesonic decays involving a neutrino as compared with those from three body decays like β-decays. Further, very recently Divakaran and Ramachandran (1982) have argued extensively that it is sufficient to take into consideration the effects of dominant mass mixing term without oscillations while considering the effects of finite neutrino mass and mass-mixing. As such, in these

Table 1. ν_τ mass values and the ratio (R) of parity non-conserving to parity-conserving terms in mesonic angular distribution of τ^- lepton decays.

Decay mode	ν_τ mass (MeV) (without mass mixing)	ν_τ mass (MeV) (with mass mixing)	R_0 (with $m_{\nu_\tau} = 0$)	R (without mass mixing but m_{ν_τ} finite)	R (with mass mixing m_{ν_τ} finite)
1. $\tau^- \to \pi^- + \nu_\tau$	610 ± 240	660 ± 260	1	$0{\cdot}97 \pm 0{\cdot}06$	$0{\cdot}96 \pm 0{\cdot}09$
2. $\tau^- \to K^- + \nu_\tau$	570 ± 210	570 ± 270	1	$0{\cdot}99 \pm 0{\cdot}03$	$0{\cdot}99 \pm 0{\cdot}05$
3. $\tau^- \to \rho^- + \nu_\tau$	700 ± 150	760 ± 170	0·04	$0{\cdot}09 \pm 0{\cdot}00$	$0{\cdot}08 \pm 0{\cdot}02$
4. $\tau^- \to K^{*-}$ (892) $+ \nu_\tau$	460 ± 440	420 ± 610	0·64	$0{\cdot}62 + 0{\cdot}02$	$0{\cdot}62 \pm 0{\cdot}01$

For the calculation of the parameters listed in this table, the values of physical constants have been used from Particle Data Group (1982), Sources for parameters not given in this booklet are referred to appropriately in the manuscript. Results, in the table, are of two-figure accuracy.

calculations we have not given any consideration to time dependent oscillation terms. The decays considered are $\tau^- \to \pi^- + \nu_T$; $\tau^- \to K^- + \nu_T$; $\tau^- \to \rho^- + \nu_T$ and $\tau^- \to K^{*-}$ (892) $+ \nu_T$. The mass limits obtained for ν_T mass are found to vary for various decays (table 1). The inclusion of experimental errors in various quantities involved in the decay probabilities contribute substantially to the statistical errors in the mass of the Tau neutrino. The theoretical predictions are not in agreement with the experimental upper limit $m_{\nu_T} < 250$ MeV (perhaps favoured) provided by DELCO group (Kirkby 1979; Flügge 1979). This does not require any serious consideration at this stage as the experimental values including the errors are expected to undergo changes with future improvement in experimental techniques and statistics.

2. Calculations of decay probability and R

2.1 *The decay* $\tau^- \to \pi^- + \nu_T$

Following the procedure of Tsai (1971), and with the inclusion of the contribution due to neutrino mass mixing (Barger *et al* 1980) treated as Dirac neutrino, we write the matrix element as (figure 1)

$$M = -i \frac{G}{\sqrt{2}} \cos \theta_1 \, |f_\pi| \sum_{i=1}^{3} U_{Ti} \, \bar{u}_{\nu i} \, \gamma^\mu (1 - \gamma 5) \, u_\tau \, q_\mu, \tag{1}$$

where U_{Ti} are the elements of the Kobayashi-Maskawa (1973) mixing mass matrix for lepton and θ_1 is the mixing angle in U_{kM} for quarks (Shrock and Wang 1978),

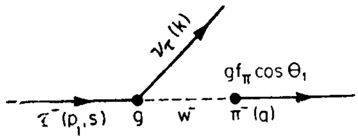

Fig 1

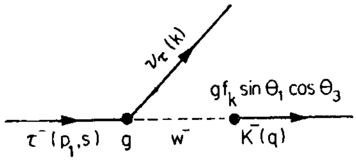

Fig. 2

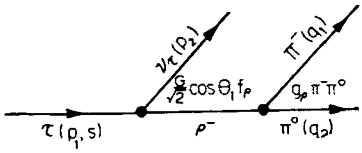

Fig 3

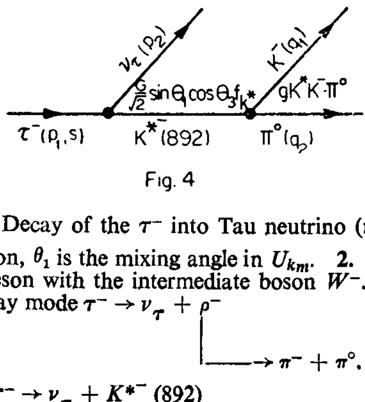

Fig. 4

Figures 1-4. **1.** Decay of the τ^- into Tau neutrino (ν_τ) and π^- meson. W^- is the intermediate boson, θ_1 is the mixing angle in U_{km}. **2.** Decay of the τ^- into Tau Neutrino and K^- meson with the intermediate boson W^-. θ_1 and θ_3 are mixing angles in U_{km}. **3.** Decay mode $\tau^- \to \nu_\tau + \rho^-$

$\qquad\qquad\qquad\quad \hookrightarrow \pi^- + \pi^0.$

4. Decay mode $\tau^- \to \nu_\tau + K^{*-}$ (892)

$\qquad\qquad\qquad\quad \hookrightarrow K^- + \pi^0.$

in u_T the subscript τ merely denotes the τ lepton spinor, and no summation over τ is implied. The differential decay probability for the polarised τ^- decay is given as

$$\mathrm{d}W = \frac{G^2|f_\tau|^2 \sum_{i=i}^{3} |U_{Ti}|^2 m_T^3}{16\pi}\left[\left(1-\frac{m_{\pi^-}^2}{m_T^2}\right)^2 + \frac{m_i^2}{m_T^2}\left(\frac{7}{2}\frac{m_i^2}{m_T^2}+\frac{m_{i-}^2}{m_T^2}-3\right)\right.$$

$$\left. + \hat{S}\cdot\hat{q}\left\{\left(1-\frac{m_{\pi^-}^2}{m_T^2}\right)^2 + \frac{m^2}{m_T^2}\left(\frac{2m_i^2}{m_T^2}+\frac{2m_{\pi^-}^2}{m_T^2}-3\right)\right\}\right]\frac{\mathrm{d}\Omega}{4\pi}\cos^2\theta_1, \quad (2)$$

where m_i denote non-degenerate neutrino masses. The total decay rate is obtained as

$$W(\tau^- \to \pi^- + \nu_\tau) = \frac{G^2 \cos^2 \theta_1 |f_\pi|^2}{16\pi} \sum_{i=1}^{3} | U_{\tau i}|^2 m_\tau^3$$

$$\times \left[\left(1 - \frac{m_{\pi^-}^2}{m_\tau^2}\right)^2 - \frac{3m_i^2}{m_\tau^2}\right], \tag{3}$$

where terms of the order of $m_{\pi^-}^4/m_\tau^4$, m_i^4/m_τ^4 etc. are neglected. The theoretical decay rate with zero neutrino mass in this order is calculated to be

$$W(\tau^- \to \pi^- + \nu_\tau) = 3{\cdot}6155 \times 10^{11}/\text{sec}. \tag{4}$$

The experimental value of this decay rate, with τ^- decay time as $(4{\cdot}6 \pm 1{\cdot}9) \times 10^{-13}$ sec and the branching fraction equal to $(10{\cdot}7 \pm 1{\cdot}6) \times 10^{-2}$, (Particle Data Group 1982) is found to be

$$W_{\text{exp}} (\tau^- \to \pi^- + \nu_\tau) = (2{\cdot}3 \pm 0{\cdot}98) \times 10^{11}/\text{sec}. \tag{5}$$

Attributing the difference in the theoretical and experimental values of the decay rate to the contribution due to the finite neutrino mass, we equate it to the theoretical expression

$$\frac{3G^2 \cos^2 \theta_1 |f_\pi|^2 m_\tau^3 \sum_{i=1}^{3} U_{\tau i}^2}{16\pi} \frac{m_i^2}{m_\tau^2}.$$

We use the solution (A) of Barger (1980) in terms of the mixing mass matrix

$$U_{\nu_i} = \begin{bmatrix} 0{\cdot}64 & 0{\cdot}66 & 0{\cdot}38 \\ -0{\cdot}72 & 0{\cdot}69 & 0{\cdot}01 \\ -0{\cdot}26 & -0{\cdot}28 & 0{\cdot}92 \end{bmatrix}, \tag{6}$$

where ν denotes e, μ, τ in our approximations.

Assuming that $m_{\nu_e} = m_1$, $m_{\nu_\mu} = m_2$ and $m_{\nu_\tau} = m_3$, we retain only $m_{\nu_\tau}^2/m_\tau^2$ term as dominant contributing term because the contribution due to $m_{\nu_e}^2/m_\tau^2$ and $m_{\nu_\mu}^2/m_\tau^2$ will be negligible (Kalyniak and Ng 1981). This enables us to determine limits on ν_τ mass which are given in table 1.

Further the ratio (R) of parity-violating to parity-conserving terms, in (2), for this process is given by

$$R = \frac{\left(1 - \frac{m_{\pi^-}^2}{m_\tau^2}\right)^2 + \frac{m_i^2}{m_\tau^2}\left(\frac{2m_i^2}{m_\tau^2} + \frac{2m_{\pi^-}^2}{m_\tau^2} - 3\right)}{\left(1 - \frac{m_{\pi^-}^2}{m_\tau^2}\right)^2 + \frac{m_i^2}{m_\tau^2}\left(\frac{7}{2}\frac{m_i^2}{m_\tau^2} + \frac{m_{\pi^-}^2}{m_\tau^2} - 3\right)}. \tag{7}$$

Using the ν_τ mass as obtained earlier, the R value for finite neutrino mass without and with mass-mixing are calculated and are given in table 1.

2.2 *The decay $\tau^- \to K^- + \nu_\tau$*

The process of calculations follow the same path as that for $\tau^- \to \pi^- + \nu_\tau$, with $f_\pi \to f_k$, $m_{\pi^-} \to m_{k^-}$ and $\cos\theta_1 \to \sin\theta_1 \cos\theta_3$ (figure 2), θ_3 is the mixing angle in U_{kM} (Shrock and Wang 1978).

The differential decay probability is given by

$$\mathrm{d}W = \frac{G^2 |f_k|^2 \sin^2\theta_1 \cos^2\theta_3}{16\pi} \sum_{i=1}^{3} |U_{\tau_i}|^2 m_\tau^3 \left[\left(1 - \frac{m_{k^-}^2}{m_\tau^2}\right)^2 + \frac{m_i^2}{m_\tau^2}\right.$$

$$\left.\left(\frac{7}{2}\frac{m_i^2}{m_\tau^2} + \frac{m_{k^-}^2}{m_\tau^2} - 3\right) + \hat{s}\cdot\hat{q}\left\{\left(1 - \frac{m_{k^-}^2}{m_\tau^2}\right)^2 + \frac{m_i^2}{m_\tau^2}\left(\frac{2m_i^2}{m_\tau^2} + \frac{2m_{k^-}^2}{m_\tau^2} - 3\right)\right\}\right]\frac{\mathrm{d}\Omega}{4\pi}, \quad (8)$$

and the total decay rate as

$$W = \frac{G^2 |f_k|^2 \sin^2\theta_1 \cos^2\theta_3}{16\pi} \sum_{i=1}^{3} |U_{\tau_i}|^2 \left[m_\tau^3\left(1 - \frac{m_{k^-}^2}{m_\tau^2}\right)^2 - 3m_i^2 m_\tau\right]. \quad (9)$$

Following the procedure of (2.1) with the use of experimental value for the τ^- decay time (Feldman *et al* 1981) $T = (4\cdot6 \pm 1\cdot9) \times 10^{-13}$ sec and the branching ratio $\approx 0\cdot5\%$ (Perl 1979), the limits on ν_τ mass and the ratio R have been calculated and tabulated in table 1. The values obtained for ν_τ mass for this case are valid to the extent of the validity of the aforesaid value of branching ratio which is not yet well established (Particle Data Group 1982).

2.3 *The decay $\tau^- \to \nu_\tau + \rho^-$*

$$\rho^- \to \pi^0 + \pi^-$$

The calculations for this decay are slightly complicated. We follow the procedure due to Tsai (1971) with the inclusion of finite neutrino mass and mass-mixing. We write for the matrix element the expression (figure 3).

$$M = g_{\tau\rho\nu}\, g_{\rho\pi^-\pi^0} \sum_{i=1}^{3} U_{\tau i}\, \bar{u}_{\nu i}\, \gamma^\lambda (1 - \gamma^5)\, u_\tau \frac{1}{(q_1 + q_2)^2 - m_\rho^2 + i\Gamma_\rho m_\rho} Q_\lambda, \quad (10)$$

with $$Q = q_1 - q_2 \text{ and } \Gamma_\rho = \frac{g_{\rho\pi^-\pi^0}^2}{48\pi^2} m_\rho \left\{1 - \frac{2(m_{\pi^-}^2 + m_{\pi^0}^2)}{m_\rho^2}\right\}^{3/2}. \quad (11)$$

Taking τ^- to be polarised and replacing the Breit-Wigner factor by a delta function, *i.e.*,

$$\left|\frac{1}{(q_1+q_2)^2 - m_\rho^2 + i\,\Gamma_\rho m_\rho}\right|^2 = \frac{\pi}{\Gamma_\rho m_\rho}\,\delta\,\{(q_1+q_2)^2 - m_\rho^2\}, \tag{12}$$

we get the following expression for the angular distribution of π^-:

$$\frac{dW}{d\Omega} = \frac{3g_{\tau\rho\nu}^2 \sum_{i=1}^{3} |U_{\tau i}|^2}{(4\pi)^2 m_\tau^2 m_\rho^2 \left(1 - 2\frac{m_{\pi^-}^2 + m_{\pi^0}^2}{m_\rho^2}\right)^{3/2}} \left[\frac{16}{3} m_\tau^2 (w_1 - A)^3 - 4m_\tau (w_1 - A)^2 D\right.$$
$$+ (m_\tau^2 - m_\rho^2 + m_i^2)\, CW_1 + (\hat{s}\cdot\hat{q}_1)\, 4m_\tau \left\{\left(\frac{4}{3} m_\tau W_1^2 - 4m_\tau w_1 A\right.\right.$$
$$\left.+ 4m_\tau A^2 + \frac{8}{3} m_{\pi^-}^2 m_\tau + Bm_\tau - AC - D(w_1 - 2A)\right) E - \left(4m_\tau m_{\pi^-}^2 A\right.$$
$$\left.\left.\left. + m_\tau AB + m_{\pi^-}^2 D + \frac{DB}{2} - \frac{C}{4}(m_\rho^2 + D)\right) \log (w_1 + E)\right\}\right]_{w_1 \min.}^{w_1 \max.}, \tag{13}$$

where

$$A = m_\tau^2 + m_\rho^2 - m_i^2/4m_\tau; \quad B = m_\rho^2 - 3m_{\pi^-}^2 - m_{\pi^0}^2;$$
$$C = m_\rho^2 - 2(m_{\pi^-}^2 + m_{\pi^0}^2); \quad D = m_{\pi^-}^2 - m_{\pi^0}^2; \quad E = (w_1^2 - m_\rho^2)^{1/2}; \tag{14}$$
$$w_{1\max.} = A\left(\frac{D}{m_\rho^2} + 1\right) + \left(A^2 - \frac{m_\rho^2}{4}\right)^{1/2}\left(1 - 2\frac{m_{\pi^-}^2 + m_{\pi^0}^2}{m_\rho^2}\right)^{1/2};$$

and

$$w_{1\min.} = A\left(\frac{D}{m_\rho^2} + 1\right) - \left(A^2 - \frac{m_\rho^2}{4}\right)^{1/2}\left(1 - 2\frac{m_{\pi^-}^2 + m_{\pi^0}^2}{m_\rho^2}\right)^{1/2}.$$

The decay rate is given by

$$W(\tau^- \to \rho^- + \nu_\tau) = \frac{G^2 \cos^2\theta_1\, m_\rho^2}{64\pi^2} \sum_{i=1}^{3} |U_{\tau_i}|^2$$
$$\times \left[m_\tau^3 (1 - m_\rho^2/m_\tau^2)^2 (1 + 2m_\rho^2/m_\tau^2) - 3\, m_i^2\, m_\tau\right], \tag{15}$$

where $g_{\tau\rho\nu} = \frac{G}{\sqrt{2}} \cos\theta_1 f_\rho$, and f_ρ (Tsai 1971) $= m_\rho^2/2\sqrt{\pi})$ have been used. Using the experimental τ^- decay time $T = (4{\cdot}6 \pm 1{\cdot}9) \times 10^{-13}$ sec and the branching ratio equal to $(21{\cdot}6 \pm 3{\cdot}6)\%$ (Particle Data Group 1982), we calculate ν_T mass and the ratio R for the process following the procedure given in § 2.1. The results are given in table 1.

2.4 *The decay* $\tau^- \to K^{*-}(892) + \nu_\tau$

$$\tau^- \to K^{*-}(892) + \nu_\tau, \quad K^{*-} \to K^- + \pi^0$$

For this process calculations follow the same path as that for $\tau^- \to \rho^- + \nu_\tau$, with the following replacements:

$$g_{\tau\rho\nu} \to g_{\tau k^*\nu};\ g_{\rho\pi^-\pi^0} \to g_{k^*k^-\pi^0};\ m_\rho \to m_{k^*};\ m_{\pi^-} \to m_{k^-};$$

$$f_\rho \to f_{k^*} \text{ and } \cos\theta_1 \to \sin\theta_1 \cos\theta_3 \text{ (figure 4).} \tag{16}$$

We obtain for the angular distribution of K^-, the expression

$$\frac{\mathrm{d}W}{\mathrm{d}\Omega} = \frac{3\, g^2_{\tau k^*\nu} \sum_{i=1}^{3} |U_{\tau_i}|^2}{(4\pi)^2\, m_\tau^2\, m_{k^*}^2 \{1 - 2\,(m_{k^-}^2 + m_{\pi^0}^2)/m_{k^*}^2\}^{3/2}}$$

$$\times \Bigg[\frac{16}{3} m_\tau^2 (w_1 - A)^3 - 4\, m_\tau (w_1 - A)^2 D$$

$$+ (m_\tau^2 - m_{k^*}^2 + m_l^2)\, CW_1 + (\hat{s}\,.\,\hat{q}_1)\, 4m_\tau \Bigg\{\Bigg(\frac{4}{3} m_\tau w_1^2 - 4m_\tau w_1 A$$

$$+ 4m_\tau A^2 + \frac{8}{3} m_{k^-}^2 m_\tau + Bm_\tau - AC - D\,(w_1 - 2A)\Bigg) E$$

$$- \Bigg(4m_\tau m_{k^-}^2 A + m_\tau AB + m_{k^-}^2 D + \frac{DB}{2} - \frac{c}{4}(m_{k^*}^2 + D)\Bigg)$$

$$\times \log(w_1 + E)\Bigg\}\Bigg]_{w_{1\,\min.}}^{w_{1\,\max.}}, \tag{17}$$

where $A, B, C, D, E, w_{1\,\max.}$ and $w_{1\,\min.}$ are identical to those given in (14) with the use of the replacement (16). The decay rate is given by

$$W(\tau^- \to \nu_\tau + K^*(892)) = \frac{G^2\, m_\rho^2 \sin^2\theta_1 \cos^2\theta_3}{64\,\pi^2} \sum_{i=1}^{3} |U_{\tau_i}|^2 \left[m_\tau^3\left(1 - \frac{m_{k^*}^2}{m_\tau^2}\right)^2\right.$$

$$\left. \times \left(1 + \frac{2m_{k^*}^2}{m_\tau^2}\right) - 3m_l^2 m_\tau\right], \tag{18}$$

where $g^2_{\tau\, k^*\, \nu}$ (Tsai 1971) $= \dfrac{G^2\, m^2_\rho\, m^2_{k^*} \sin^2 \theta_1 \cos^2 \theta_3}{8\pi}$.

Using the experimental τ^- decay time $T = (4\cdot 6 \pm 1\cdot 9) \times 10^{-13}$ sec and the branching ratio equal to $(1\cdot 7 \pm 0\cdot 7) \times 10^{-2}$ (Particle Data Group 1982), we calculate the ν_τ mass and the ratio R for this process following the procedure given in § 2·1. The results are given in table 1.

The values of ν_τ mass obtained from this decay involve large errors so much so that when mixing is included, the lower limit becomes negative. This is because of (i) large errors in the experimental values of decay time and the branching ratio for this decay and (ii) type of mixing used. The values quoted in table 1 are with the use of KM mixing. Instead, if the hierarchical mixing is used (Kalyanik and Ng 1981), the ν_τ mass limits are found to be (400 ± 580) MeV. Further if one replaces $\cos \theta_1$ by $\cos \theta_c$ and $\sin \theta_1 \cos \theta_3$ by $\sin \theta_c$, θ_c being the Cabibbo angle (Cabibbo 1963), one finds these mass-limits as (500 ± 480) MeV and (470 ± 460) MeV for KM mixing and hierarchical mixing respectively.

3. Conclusion

The ν_τ mass limits calculated for the four decays are not consistent with the experimental upper bound < 250 MeV (perhaps favoured) provided by DELCO group (Flügge 1979 and Kirkby 1979). But with the exclusion of errors, the finite masses are nearly consistent with the SLAC-LBL limit of 600 MeV (Perl *et al* 1977b) and PLUTO limit of 540 MeV (Knies 1977). The large errors in ν_τ mass values calculated are because of the large errors in the experimental parameters used in the calculations. In particular, the errors in lifetime, branching ratio and the mixing angles contribute substantially. These errors used along with KM mixing in the decay $\tau^- \to K^{*-}(892) + \nu_\tau$, renders the lower ν_τ mass limit unphysical. The discussion following relation (18) shows that in this case the type of mixing used also plays a significant role.

In view of the large uncertainties of the experimentally measured parameters, the agreement of the ν_τ mass limit with the experimental upper bound may be considered fortuitous. As such, the lack of agreement with the experimental upper bound of ν_T mass < 250 MeV, is no disaster for the theory. With the availability of more reliable experimental data and improved statistics, these limits will undergo changes. The main result of this work is essentially an upper limit on the mass of ν_τ, of the order of 700 MeV.

The R values ≈ 1, for the decays $\tau^- \to \pi^- + \nu_\tau$, and $\tau^- \to K^- + \nu_\tau$, show that these decays are purely of weak origin with maximal parity violation, the contribution from mass mixing being insignificant. For the decay $\tau^- \to K^{*-}(892) + \nu_\tau$, reduction in the R value from one may be because of contribution from the strong decay $K^{*-}(892) \to K^- + \pi^0$. The value $R \approx 0$ for the decay $\tau^- \to \rho^- + \nu_\tau$ is because of the kinematical factors, namely, the near zero difference in π^- and π^0 masses which is not the case with K^- and π^0 masses involved in the decay $\tau^- \to K^{*-}(892) + \nu_\tau$.

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