# Rare t-quark decays in the minimal four color symmetry model

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**Abstract**

The rare t-quark decays $t \to c\, l_j^+\, l_k^-$ , $t \to c\, \tilde{\nu}_j\, \nu_k$ via the scalar leptoquark doublets are investigated in the minimal four color symmetry model with the Higgs mechanism of the quark-lepton mass splitting. The total width of the charged lepton mode $\Gamma(t \to c\, l^{+'}\, l^-) = \sum_{j,k} \Gamma(t \to c\, l_j^+\, l_k^-)$ and that of the neutrino one $\Gamma(t \to c\, \tilde{\nu}'\, \nu) = \sum_{j,k} \Gamma(t \to c\, \tilde{\nu}_j\, \nu_k)$ are found and the corresponding branching ratios are shown to be

$$Br(t \to c\, l^{+'}\, l^-) \approx (3.5 - 0.4) \cdot 10^{-5},$$
$$Br(t \to c\, \tilde{\nu}'\, \nu) \approx (7.1 - 0.8) \cdot 10^{-5}$$

for the scalar leptoquark masses $m_S = 180 - 250$ GeV and for the appropriate values ($\sin\beta \approx 0.2$) of the mixing angle of the model.

The search for the possible sings of a new physics beyond the Standard Model (SM) is one of the goals of the high energy physics now. Putting LHC into operation will give the possibility to search for the non-SM effects in the top physics [1, 2], in particular, to search the rare nonstandard t-quark decays such as the FCNC decays $t \to cX$, $X = \gamma, Z, g, H$. These decays are very suppressed in the SM ($Br_{SM}(t \to cX) \sim 10^{-13}$ and $\sim 10^{-11}$ for

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$X = \gamma, Z, H$ and for $X = g$ [3–5]) but they can be essentialy enhanced in some extensions of the SM. For example, in the minimal supersymmetric standard model (MSSM) the branching ratios of these decays can amount to the values $Br_{MSSM}(t \to cX) \sim 10^{-8}, \sim 10^{-6}, \sim 10^{-4}$ for $X = \gamma, Z$, $X = g$, $X = h^0$ [6–12], in the two Higgs doublet model they can be enhanced up to $Br_{2HDM}(t \to cX) \sim 10^{-7}, \sim 10^{-8}, \sim 10^{-5}, \sim 10^{-4}$ for $X = \gamma, Z, g, h$ [3, 13, 14], some ehancement of these decays can also take place in the model with additional quark singlets [15]. The detection of such rare decays an LHC would be an evident signal of new physics beyond the SM.

One of the possible variant of new physics beyond the SM can be the variant induced by the four color symmetry between quarks and leptons of Pati-Salam type [16]. The immediate consequence of this symmetry is the prediction of the gauge leptoquarks which, however, occur to be relatively heavy. It should be noted however that in addition to the gauge leptoquarks the four color symmetry can predict also the new particles in the scalar sector. Thus, in the case of the Higgs mechanism of splitting the masses of quarks and leptons the four color symmetry in its minimal realization on the gauge group

$$G = SU_V(4) \times SU_L(2) \times U_R(1) \tag{1}$$

(MQLS-model [17, 18]) predicts the existence of the two scalar leptoquark doublets $S^{(\pm)}$ belonging to the (15,2,1) - multiplet of the group G. Unlike the vector leptoquarks the scalar leptoquark doublets $S^{(\pm)}$ can be relatively light, with masses of order of 400 GeV or less, without any contradictions with the $K_L^0 \to \mu^{\pm} e^{\mp}$ data or with the radiative correction limits [19, 20]. Because of their Higgs origin the coupling constants of these scalar leptoquark doublets with the fermions are proportional to the ratios $m_f/\eta$ of the fermion masses $m_f$ to the SM VEV $\eta$. The effects of these scalar leptoquarks in the processes with the ordinary u-, d-, s- quarks are small because of the smallness of the corresponding coupling constants ($m_u/\eta \sim m_d/\eta \sim 10^{-5}, m_s/\eta \sim 10^{-3}$), whereas these effects can be significant in c-, b- and, especially, in top-physics ( $m_c/\eta \sim m_b/\eta \sim 10^{-2}$, $m_t/\eta \sim 0.7$).

Ones of the possible new effects which can be induced be the scalar leptoquark doublets $S^{(\pm)}$ are the specific decays of t-quark

$$t \to c\, l_j^+\, l_k^- \ , \tag{2}$$

$$t \to c\, \tilde{\nu_j}\, \nu_k \tag{3}$$

with the production of c-quark with the pairs $l_j^+ l_k^-$ $j,k = 1,2,3$ of charged leptons $l_k^- = e^-$, $\mu^-$, $\tau^-$ and antileptons $l_j^+ = e^+$, $\mu^+$, $\tau^+$, in general of the different generation, or with the neutrino-antineutrino pairs $\tilde{\nu}_j \nu_k$, $\nu_k$ are the mass eigenstates of neutrinos, $\tilde{\nu}_j$ are the antineutrinos.

In this talk I would like to present the results of calculations of the contributions of the scalar leptoquark doublets $S^{(\pm)}$ into decays (2), (3) in frame of the minimal four color quark-lepton symmetry model with the Higgs mechanism of splitting the masses of quarks and leptons(MQLS-model [17, 18]) and I will discuss the numerical estimations of the branching ratios of these decays in dependence on the scalar leptoquark masses and on the mixing parameters of the model.

The minimal quark lepton symmetry model (MQLS-model [17, 18]) is based on the gauge group (1). In this model the basic left ($L$) and right ($R$) quarks $Q'^{L,R}_{ia\alpha}$ and leptons $l'^{L,R}_{ia}$ form the fundamental quartets of $SU_V(4)$ color group and can be written, in general, as superpositions

$$Q'^{L,R}_{ia\alpha} = \sum_j (A^{L,R}_{Q_a})_{ij}\, Q^{L,R}_{ja\alpha}, \qquad l'^{L,R}_{ia} = \sum_j (A^{L,R}_{l_a})_{ij}\, l^{L,R}_{ja} \tag{4}$$

of the quark and lepton mass eigenstates $Q^{L,R}_{ia\alpha}$ , $l^{L,R}_{ia}$, where $i, j = 1,\ 2,\ 3$ are the generation indexes, $a = 1,2$ and $\alpha = 1,2,3$ are the $SU_L(2)$ - and $SU_c(3)$ - indexes, $Q_{i1} \equiv u_i = (u,c,t)$, $Q_{i2} \equiv d_i = (d,s,b)$ are the up and down quarks, $l_{j1} \equiv \nu_j$ are the mass eigenstates of neutrinos and $l_{j2} \equiv l_j = (e^-, \mu^-, \tau^-)$ are the charged leptons. The unitary matrixes $A^{L,R}_{Q_a}$ and $A^{L,R}_{l_a}$ describe the fermion mixing and diagonalize the mass matrixes of quarks and leptons.

The Higgs mechanism used in MQLS-model for splitting the masses of quarks from those of leptons needs two scalar multiplets $\Phi^{(2)}$ and $\Phi^{(3)}$ with VEVs $\eta_2$ and $\eta_3$ and transforming as (1,2,1) and (15, 2, 1) multiplets of the group (1). The multiplet $\Phi^{(3)}$ contains two colored scalar leptoquark doublets $S^{(\pm)}$, octet $F$ of the scalar gluon doublets and the colorless scalar doublet $\Phi^{(3)}_{15}$ which in admixture with the (1,2,1) - doublet $\Phi^{(2)}$ form the SM Higgs doublet $\Phi^{(SM)}$ with the SM VEV $\eta = \sqrt{\eta_2^2 + \eta_3^2}$ and an additional scalar doublet $\Phi'$. All these particles are necessary for suppressing the dangerous increase of the amplitudes with the longitudinal gauge particles [21].

The scalar leptoquark doublets $S^{(\pm)}$ have the SM hypercharge $Y^{SM}_{\pm} = 1 \pm 4/3$ and can be written in the form

$$S^{(\pm)}_{a\alpha} = \begin{pmatrix} S^{(\pm)}_{1\alpha} \\ S^{(\pm)}_{2\alpha} \end{pmatrix}, \tag{5}$$

where the up ($a=1$) leptoquarks $S_{1\alpha}^{(\pm)}$ have electric charge 5/3 and 1/3 and the down ($a=2$) leptoquarks $S_{2\alpha}^{(\pm)}$ have the charge $\pm 2/3$. In general case the scalar leptoquarks $S_{2\alpha}^{(+)}$ and $\overset{*}{S}{}_{2\alpha}^{(-)}$ with electric charge 2/3 are mixed and can be written as superpositions

$$S_{2\alpha}^{(+)} = \sum_{m=0}^{3} c_m^{(+)} S_m, \qquad \overset{*}{S}{}_2^{(-)} = \sum_{m=0}^{3} c_m^{(-)} S_m \tag{6}$$

of three physical scalar leptoquarks $S_1$, $S_2$, $S_3$ with electric charge 2/3 and a small admixture of the Goldstone mode $S_0$. Here $c_m^{(\pm)}$, $m = 0,1,2,3$ are the elements of the unitary scalar leptoquark mixing matrix, $|c_0^{(\pm)}|^2 = \frac{1}{3} g_4^2 \eta_3^2 / m_V^2 \ll 1$, $g_4$ is the $SU_V(4)$ gauge coupling constant and $m_V$ is the vector leptoquark mass.

The responsible for the t-quark decays (2), (3) interactions of scalar leptoquarks (5), (6) with quarks and leptons can be written in the form

$$L_{S_1^{(+)} Q_1 l_2} = \bar{Q}_{i1\alpha}\Big[h_{ij}^L P_L + h_{ij}^R P_R\Big] l_{j2} S_{1\alpha}^{(+)} + \text{h.c.}, \tag{7}$$

$$L_{S_m Q_a l_a} = \bar{Q}_{ia\alpha}\Big[(h_{am}^L)_{ij} P_L + (h_{am}^R)_{ij} P_R\Big] l_{ja} S_{m\alpha} + \text{h.c.}, \tag{8}$$

where $P_{L,R} = (1 \pm \gamma_5)/2$ are the left and right projection operators and $(h^{L,R})_{ij}$ and $(h_{am}^{L,R})_{ij}$ are the corresponding coupling constants. As a result of the Higgs mechanism of splitting the masses of quarks and leptons the MQLS-model gives for these couplings the expressions

$$\begin{aligned}(h^L)_{ij} &= (h_1^L C_l)_{ij}\,, \quad (h^R)_{ij} = -(C_Q h_2^R)_{ij}\,, \quad (h_{am}^{L,R})_{ij} \\ &= -(h_a^{L,R})_{ij}\, c_{am}^{L,R}\,,\end{aligned} \tag{9}$$

where $C_Q = (A_{Q_1}^L)^\dagger A_{Q_2}^L$ is the CKM-matrix, $C_l = (A_{l_1}^L)^\dagger A_{l_2}^L$ is the analogous matrix in the lepton sector, $c_{1m}^{L,R} = c_m^{(\pm)}$, $c_{2m}^{L,R} = c_m^{(\mp)}$, $c_m^{(\pm)}$ are the elements of the scalar leptoquark mixing matrix in (6) and

$$(h_a^{L,R})_{ij} = \sqrt{\frac{3}{2}}\frac{1}{\eta \sin\beta}(M_{Q_a} K_a^{L,R} - K_a^{R,L} M_{l_a})_{ij}\,, \tag{10}$$

where $(M_{f_a})_{ij} = m_{f_{ia}} \delta_{ij}$ are the diagonal mass matrixes of quarks and leptons, $f_{ia} = Q_{ia}$, $l_{ia}$, $K_a^{L,R} = (A_{Q_a}^{L,R})^\dagger A_{l_a}^{L,R}$ are the mixing matrixes specific for the model with the four color quark-lepton symmetry, $\beta$ is the $\Phi^{(2)} - \Phi_{15}^{(3)}$ mixing angle, $\tan\beta = \eta_3/\eta_2$.

The interactions (7), (8) induce in the tree approximation the t-quark decays

$$t \to u_i\, l_j^+\, l_k^- \,, \tag{11}$$

$$t \to u_i\, \tilde{\nu}_j\, \nu_k \tag{12}$$

with the production of the up quarks $u_i = (u, c)$, $i = 1, 2$ according to the diagrams on Fig.1 .

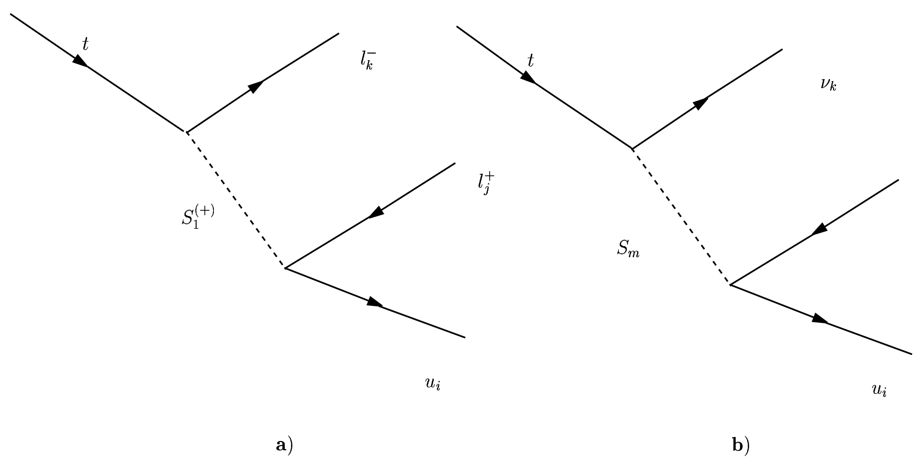


Figure 1: The diagrams of the rare t-quark decays a) $t \to u_i\, l_j^+\, l_k^-$ and b) $t \to u_i\, \tilde{\nu}_j\, \nu_k$ via scalar leptoquarks $S_1^{(+)}$ and $S_m$, $m = 1, 2, 3$ of the MQLS-model.

We have calculated the widths of the decays (11), (12) with neglect of the final fermion masses

$$m_{u_i}, m_{l_j}, m_{\nu_k} \ll m_t, m_{S_1^{(+)}}, m_{S_m} \tag{13}$$

and assuming that

$$m_{S_1^{(+)}}, m_{S_m} > m_t \,. \tag{14}$$

The resulted widths of the decays (11), (12) with the final c-quark occur to be the largest ones and can be written as

$$\Gamma(t \to c\, l_j^+\, l_k^-) \;\; = \;\; m_t \frac{\gamma_{tc}}{\sin^4\beta} k_{2j} k_{3k} f_1(\mu_{S_1^{(+)}}) \,, \tag{15}$$

$$\Gamma(t \to c\,\tilde{\nu}_j\,\nu_k) \;=\; m_t \frac{\gamma_{tc}}{\sin^4\beta} \sum_{m,n=1}^{3} k_{2j}^{mn} k_{3k}^{mn} f_2(\mu_{S_m}, \mu_{S_n})\,, \tag{16}$$

where

$$\begin{aligned}
\gamma_{tc} &= \frac{9}{512(2\pi)^3} \cdot \frac{m_t^2 m_c^2}{\eta^4}\,, && (17)\\
k_{i'j} &= |(K_1^L C_l)_{i'j}|^2\,, && (18)\\
k_{i'j}^{mn} &= |(K_1^L)_{i'j}|^2 c_m^{*(+)} c_n^{(+)} + |(K_1^R)_{i'j}|^2 c_m^{(-)} c_n^{*(-)}\,, && (19)\\
& \qquad i', j = 1,2,3,
\end{aligned}$$

and

$$\begin{aligned}
f_1(\mu) &= 6\mu^2 - 5 - 2(\mu^2-1)(3\mu^2-1)\ln\frac{\mu^2}{\mu^2-1}\,, && (20)\\
f_2(\mu_1,\mu_2) &= 2(\mu_1^2+\mu_2^2) - 3 - 2\frac{\mu_1^2(\mu_1^2-1)^2}{\mu_1^2-\mu_2^2}\ln\frac{\mu_1^2}{\mu_1^2-1}\\
& \quad -2\frac{\mu_2^2(\mu_2^2-1)^2}{\mu_2^2-\mu_1^2}\ln\frac{\mu_2^2}{\mu_2^2-1}\,, && (21)
\end{aligned}$$

$\mu_{S_1^{(+)}} = m_{S_1^{(+)}}/m_t$ , $\mu_{S_m} = m_{S_m}/m_t$ .

The eq. (15) predicts the $t \to c\,l_j^+\,l_k^-$ decays with the production of the generation diagonal charged lepton pairs $e^+e^-, \mu^+\mu^-, \tau^+\tau^-$ as well as of the non-diagonal ones such as $e^+\mu^-, \mu^+e^-, e^+\tau^-, \ldots$ in dependence on the fermion mixing parameters $k_{2j}$, $k_{3k}$.

Summarizing the partial widths (15), (16) over the generation indexes and using the unitarity of the matrixes $K_1^{L,R}$, $C_l$ we obtain the total width of the charged lepton mode and that of the neutrino one in the fermion mixing independent form

$$\Gamma(t \to c\,l^{+'}\,l^-) = \sum_{j,k} \Gamma(t \to c\,l_j^{+'}\,l_k^-) = m_t \frac{\gamma_{tc}}{\sin^4\beta} f_1(\mu_{S_1^{(+)}})\,, \tag{22}$$

$$\begin{aligned}
\Gamma(t \to c\,\tilde{\nu}'\nu) &= \sum_{j,k} \Gamma(t \to c\,\tilde{\nu}_j\,\nu_k)\\
&= m_t \frac{\gamma_{tc}}{\sin^4\beta} \sum_{m,n=1}^{3} k^{mn} f_2(\mu_{S_m}, \mu_{S_n})\,. && (23)
\end{aligned}$$

The total width of the charged lepton mode (22) includes all the decays with the production of the every possible charged lepton pairs both the generation diagonal and non-diagonal ones. In particular case of the zero fermion mixing ($K_1^L C_l = I$) the total width (22) is saturated by the non-diagonal decay $t \to c\,\mu^+\,\tau^-$ which is in this case the only allowed decay of type (2).

The total width of the neutrino mode (23) contains the parameters $k^{mn} = (c_m^{(+)} c_n^{*(+)} + c_m^{(-)} c_n^{*(-)})^2$ depending on the scalar leptoquark mixing (6). The expression (23) can be simplified in the particular case of the scalar leptoquark mixing (6) with $c_3^{(\pm)} = 0$ when $S_2^{(+)}$ and $\overset{*}{S}{}_2^{(-)}$ are approximately the superpositions of two physical scalar leptoquarks $S_1$ and $S_2$ (the small admixture of the Goldstone mode can be neglected because of the smallness of $c_0^{(\pm)}$). In this case $k^{mn} \approx \delta_{mn}$ for $m, n = 1, 2$ and the width (23) takes the form

$$\Gamma(t \to c\,\tilde{\nu}'\nu) = m_t \frac{\gamma_{tc}}{\sin^4\beta}[f_1(\mu_{S_1}) + f_1(\mu_{S_2})]\,, \tag{24}$$

here the relation $f_2(\mu, \mu) = f_1(\mu)$ has been taken also into account.

The widths (22), (24) depend on the masses $m_{S_1^{(+)}}$, $m_{S_1}$, $m_{S_2}$ of the scalar leptoquarks and on the $\Phi^{(2)} - \Phi_{15}^{(3)}$ mixing angle $\beta$.

The current data on the direct search for the leptoquarks set the lower mass limits [22]

$$m_{LQ} > 242\,\mathrm{GeV},\ 202\,\mathrm{GeV}, 148\,\mathrm{GeV} \tag{25}$$

for the scalar leptoquarks of the first, of the second and the of third generation respectively. As mentioned above the scalar leptoquarks $m_{S_1^{(+)}}$, $m_{S_1}$, $m_{S_2}$ couple most intensively with t-quark. In the case (14) they will decay predominantly into $t\,\tilde{l}_{ja}$ pairs and should be regarded as the third generation ones. In this case the condition (14) is consistent with lower experimental limit 148 GeV in (25) and we use (14) when choosing the lower scale leptoquark masses in (22), (24). With account of the total width of t-quark $\Gamma_t^{tot} \approx \Gamma(t \to bW) \approx 1.56$ GeV we obtain from (22), (24) that

$$Br(t \to c\,l^{+'}\,l^-) = (5.7 \cdot 10^{-8} - 0.6 \cdot 10^{-8} - 0.7 \cdot 10^{-9})/\,/\sin^4\beta\,, \tag{26}$$

$$Br(t \to c\,\tilde{\nu}'\,\nu) = (11.3 \cdot 10^{-8} - 1.2 \cdot 10^{-8} - 1.4 \cdot 10^{-9})/\,/\sin^4\beta \tag{27}$$

for $m_{S_1^{(+)}}$, $m_{S_1}$, $m_{S_2} = 180 - 250 - 400\,\mathrm{GeV}$.

The mixing angle $\beta$ enters into the coupling constants (9), (10) and we restrict it by the smallness of the pertubation theory parameter

$$(h^{S,P})^2/4\pi < 1\,, \tag{28}$$

where $h^{S,P} = (h^L \pm h^R)/2$ are the scalar and pseudoscalar coupling constants and $h^{L,R}$ are the chiral coupling constants (9), (10). With account of the t-quark chiral coupling constants in (9), (10) as of the largest ones the condition (28) gives that $\sin\beta > 0.12$.

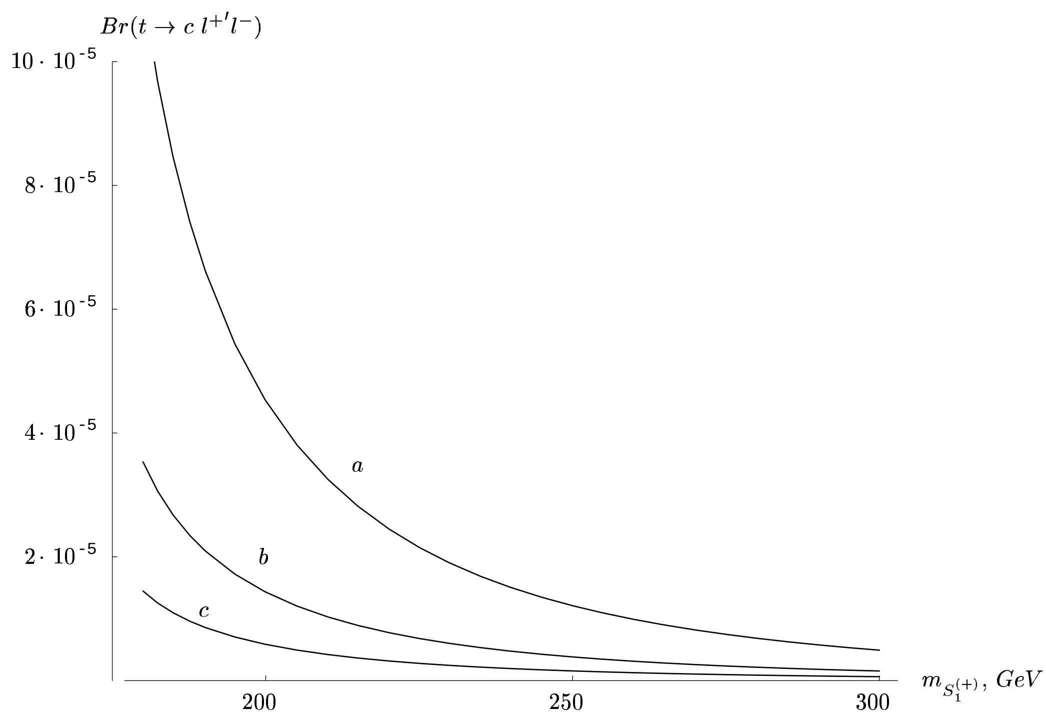


Figure 2: The branching ratio $Br(t \to c\, l^{+\prime}\, l^-) = \sum_{j,k} Br(t \to c\, l_j^+\, l_k^-)$ of the charged lepton mode as a function of the scalar leptoquark mass $m_{S_1^{(+)}}$ for a) $\sin\beta = 0.15$, b) $\sin\beta = 0.20$, c) $\sin\beta = 0.25$.

The Fig.2 shows the branching ratio $Br(t \to c\, l^{+\prime}\, l^-)$ of the charged lepton mode as the function of the scalar leptoquark mass $m_{S_1^{(+)}} = 180 - 300$ GeV for a) $\sin\beta = 0.15$, b) $\sin\beta = 0.2$ and c) $\sin\beta = 0.25$. The corresponding branching ratios $Br(t \to c\,\tilde{\nu}'\,\nu)$ of the neutrino mode for $m_{S_1} = m_{S_2} = 180 - 300$ GeV are twice as large as those of the charged lepton mode.

As is seen from the Fig.2 in all three cases a), b) and c) there is the mass region with $Br(t \to c\,l^{+'}\,l^-) \sim 10^{-5}$.

For example for $\sin\beta = 0.2$ from Fig.2-b and from (26), (27) we obtain

$$Br(t \to c\,l^{+'}\,l^-) = (3.5 - 0.4) \cdot 10^{-5}, \tag{29}$$

$$Br(t \to c\,\tilde{\nu}'\,\nu) = (7.1 - 0.8) \cdot 10^{-5} \tag{30}$$

for $m_{S_1^{(+)}}$, $m_{S_1}$, $m_{S_2} = 180 - 250$ GeV.

As is seen from (29), (30) and from Fig.2 the branching ratios of the decays under consideration can be close to the sensitivity of LHC to the $t \to cX$ decays $Br(t \to cX) > 5 \cdot 10^{-5}$ [1, 2, 12, 23] and the search for the decays $t \to c\,l_j^+\,l_k^-$, $t \to c\,\tilde{\nu}_j\,\nu_k$ at LHC may be of interest. The detection of such decays including the generation non-diagonal ones such as $t \to c\,\mu^+\,\tau^-$ etc. would be the clear sign of the new physics, possibly, induced by the four color symmetry between quarks and leptons.

In conclusion we resume the results of the work.

The rare t-quark decays $t \to c\,l_j^+\,l_k^-$, $t \to c\,\tilde{\nu}_j\,\nu_k$ induced by the scalar leptoquark doublets in the minimal four color symmetry model with the Higgs mechanism of the quark-lepton mass splitting are investigated .

The branching ratios of the charged lepton mode and of the neutrino one are found in the fermion mixing independent form and they are shown to be of order of $10^{-5}$ for the scalar leptoquark masses $m_{S_1^{(+)}}$, $m_{S_1}$, $m_{S_2} = 180-250$ GeV and for appropriate values ($\sin\beta \approx 0.2$) of the mixing angle of the model (see eqs.(29), (30) ).

These estimations are close to the sensitivity $Br(t \to cX) > 5 \cdot 10^{-5}$ of LHC to the $t \to cX$ $(X = \gamma, Z, g, H)$ decays and the search for the decays $t \to c\,l_j^+\,l_k^-$, $t \to c\,\tilde{\nu}_j\,\nu_k$ at LHC seems to be of interest.

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