Probing new physics in rare charm processes\footnote{Talk at the Cairo International Conference on High Energy Physics, 9-14 January 2001, Cairo, Egypt}

S. Prelovsek

Department of Physics, University of Ljubljana and J. Stefan Institute, Ljubljana, Slovenia
E-mail: sasa.prelovsek@ijs.si

ABSTRACT

We explore the sensitivity of the flavour changing neutral current transitions among $c$ and $u$ quarks in the context of the Minimal Supersymmetric Standard Model. The standard model rate for $c \to u\gamma$ can be enhanced by up to two orders of magnitudes in general MSSM, while the $c \to ul^+l^-$ rate can be enhanced by at most a factor of three. The most suitable hadronic observable to probe the $c \to u\gamma$ transition is the decay $B_c \to B_u^*\gamma$ or the difference in decay rates of $D^0 \to \rho^0\gamma$ and $D^0 \to \omega\gamma$, since they are relatively free of the long distance contributions. The $c \to ul^+l^-$ transition may be probed in $D \to \pi l^+l^-$ decays at high di-lepton mass and we predict the long distance contributions for these modes.

1 Introduction

Flavour changing neutral (FCN) currents occur in the standard model only at the loop level where they are suppressed by the GIM mechanism. The FCN transitions among the up-like quarks $u$, $c$ and $t$ are especially rare due to the small masses of the intermediate down-like quarks and only the upper experimental limits for this processes are available at present \cite{1,2,3,4}. In the present paper we turn to the FCN transitions among the up-like quarks with the highest branching ratio in the standard model, namely the $c \to u\gamma$ and $c \to ul^+l^-$ transitions. We do not discuss the decays $c \to ug$ and $c \to u\nu\bar{\nu}$ which would hardly lead to a distinctive experimental signature, or the helicity suppressed decay $D^0 \to l^+l^-$. The $D^0 - \bar{D}^0$ mixing has been thoroughly studied with the predictions compiled in \cite{5} and the new exciting experimental data presented in \cite{6}.

The FCN processes are suitable as probes for the popular low energy supersymmetry, which has various new sources of flavour violation. Such investigation may reveal the flavour structure of the soft supersymmetry breaking terms and shed light on the mechanism of SUSY breaking. In this note we explore the sensitivity of the $c \to u\gamma$ \footnote{Talk at the Cairo International Conference on High Energy Physics, 9-14 January 2001, Cairo, Egypt} and $c \to ul^+l^-$ \footnote{Talk at the Cairo International Conference on High Energy Physics, 9-14 January 2001, Cairo, Egypt} decay rates in the framework of the minimal supersymmetric standard model (MSSM).
The effect of new physics on the quark decay of interest may be overshadowed by the more mundane effects of the long distance (LD) dynamics in hadron decays. The least contaminated LD hadronic observable to probe $c \to u \gamma$ transition is found to be the decay $B_c \to B^*_u \gamma$ or the difference of the decay rates $D^0 \to \rho \gamma$ and $D^0 \to \omega \gamma$. Probing $c \to ul^+l^-$ might be possible at high $m_{ll}$ in $D \to \pi l^+l^-$ decay.

The SM and MSSM predictions for the $c \to u \gamma$ and $c \to ul^+l^-$ rates are given in Section 2, while the interesting hadronic observables are discussed in Section 3. Conclusions are drawn in Section 4.

2 $c \to u \gamma$ and $c \to ul^+l^-$ decays

2.1 Standard model

The $c \to u \gamma$ amplitude is strongly GIM suppressed at one loop electroweak order, $A(c \to u \gamma) \propto \sum_{d,s,b} V^*_{cq} V_{uq} m^2_q$, leading to a branching ratio of only $\sim 10^{-18}$. The two-loop QCD corrections to the responsible Wilson coefficient $c_7$ were found to be large $^{12}$, leading to

$$Br^{SM}(c \to u \gamma) \simeq 3 \times 10^{-8}. \quad (1)$$

The dominant contribution to $c \to ul^+l^-$ at the one-loop electroweak level is not strongly GIM suppressed $^{8, 11}$, $A(c \to ul^+l^-) \propto V^*_{cs} V_{us} \ln[m^2_s/m^2_d]$, leading to

$$Br^{SM}(c \to ul^+l^-) \simeq 6 \times 10^{-9}. \quad (2)$$

The two-loop QCD corrections to $c_7$ $^{12}$ do not affect the rate significantly, as shown in Fig. 1.

![Figure 1](image-url)

Figure 1: The differential branching ratio $dBr(c \to ul^+l^-)/ds$ with $s = m_{ll}^2/m_c^2$: the dashed line denotes the one-loop standard model prediction, while the solid line incorporates also the QCD corrections to the Wilson coefficient $c_7$ $^{12}$. The best possible enhancement of the $c \to ul^+l^-$ rate in the general MSSM is displayed by the dot-dashed line, where the mass insertions are taken at their maximal values $^{3}, \ (4)$. Masses of squarks and gluinos are taken at 250 GeV and $\alpha_s = 0.12$. 

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2.2 Minimal supersymmetric standard model

New sources of flavour violation are present in the minimal supersymmetric standard model (MSSM) and these depend crucially on the mechanism of the supersymmetry breaking. The schemes with flavour-universal soft-breaking terms lead to contributions proportional to \( \sum_{q=d,s,b} V_{cq} V_{us} m_q^2 \) \(^{(13)}\) and have negligible effect on the \( c \to u \gamma \) and \( c \to u^+ l^- \) rates \(^{(4)}\). Our purpose here is to explore the largest possible enhancement of the \( c \to u \gamma \) and \( c \to u^+ l^- \) rates in MSSM with unbroken R-parity and arbitrary non-universal soft breaking terms.

The first analysis of the \( c \to u \gamma \) decay in MSSM has been presented in \(^{(14)}\), where only the additional penguin diagrams with gluinos in the loop were considered. The complete analysis, including the QCD corrections, for the penguin diagrams with gluinos, charginos and neutralinos in the loop was presented in \(^{(7)}\). We choose the super-CKM basis for squarks, in which the quark - squark - gaugino vertex has the same flavour structure as the quark - quark - gauge boson vertex, and undertake the mass insertion approximation. In this framework, the flavour change is provided by the non-diagonality of the squark propagators and is parameterized by \( (\delta_q^{ij})_{AB} = (\mathcal{M}^2_{ij})_{AB}^q / m_q^2 \) with \( A, B = L, R \) and squark mass matrix squared \( (\mathcal{M}^2)^q_{AB} \). The diagram, that eventually turns out to give the dominant contribution, is shown in Fig. 2.

\[ \begin{array}{c}
 c_R & \rightarrow & u_L \\
 (\delta^{12}_{LR}) & & (\delta^{12}_{RL}) \\
 c_L & \rightarrow & u_R \\
 \end{array} \]

Figure 2: The diagram giving the dominant supersymmetric contribution to \( c \to u \gamma \) and \( c \to u^+ l^- \) decays in general MSSM, given the constraints \(^{(3)}\) and \(^{(4)}\) on the mass insertions.

The mass insertions are free parameters in a general MSSM. The strongest upper bound on \( |\delta^{12}_{LR}| \) comes by requiring that the minima of the scalar potential do not break charge or color, and that they are bounded from bellow \(^{(7)},^{(15)}\)

\[ |\delta^{u}_{12}|_{LR}, |\delta^{u}_{12}|_{RL} \leq 0.0046 \quad \text{for} \quad M_{sq} = 250 \text{ GeV}. \]  \(^{(3)}\)

The insertions \( (\delta_{12}^{u})_{LL} \) and \( (\delta_{12}^{u})_{RR} \) can be bounded by saturating the experimental upper bound \( \Delta m_D < 4.5 \times 10^{-14} \text{ GeV} \) \(^{(3)}\) by the gluino exchange \(^{(7)},^{(16)}\). Since we are interested in exhibiting the largest possible enhancement, we saturate \( \Delta m_D \) by \( (\delta_{12}^{u})_{LL} \) \(^{(7)},^{(16)}\)

\[ |\delta^{u}_{12}|_{LL} \leq 0.03 \quad \text{for} \quad M_{sq} = M_{gl} = 250 \text{ GeV} \]  \(^{(4)}\)

and set \( (\delta_{12}^{u})_{RR} = 0 \).

The scatter plot of the \( c \to u \gamma \) branching ratio that result from the gluino, chargino and neutralino contributions is shown in Fig. 3, where the mass insertions are taken at the maximal values of \(^{(3)}\) and \(^{(4)}\). If \( (\delta_{12}^{u})_{LR} \) is close to the upper value in \(^{(3)}\), the gluino
Figure 3: The scatter plot of predicted $c \to u\gamma$ branching ratios for various contributions in MSSM. The QCD-corrected [12] standard model rate [1] is represented by the dot on the left. The remaining dots represent the rates arising solely from gluino, chargino and neutralino exchange; the contributions arising from $LL$ and $LR$ insertions are shown separately. The mass insertions are taken at their maximal values (3) and (4), while other parameters are taken in the ranges $250 \text{ GeV} \leq m_{\tilde{q}}, m_{\tilde{g}} \leq 1000 \text{ GeV}$, $\alpha_s = 0.12$, $2.5 \leq \tan \beta \leq 30$, $100 \text{ GeV} \leq |\mu| \leq 300 \text{ GeV}$ and $m_{\chi^+_{1}} > 90 \text{ GeV}$.

exchange diagram in Fig. 2 can enhance the standard model rate [1] by up to two orders of magnitudes

$$Br(c \to u\gamma)_{LR} \approx 6 \times 10^{-6}.$$  (5)

In contrast, the contributions from chargino and neutralino remain at least an order of magnitude below the QCD corrected standard model rate.

Based on experience from $c \to u\gamma$, we consider only the gluino exchange diagrams with a single mass insertion for the case of $c \to ul^+l^-$ decay. The dominant contribution again arises from the diagrams in Fig. 3 with the lepton pair attached to the photon. The best possible enhancement in general MSSM is shown by dot-dashed line in Fig. 1. The effect is sizeable at small di-lepton mass and can enhance the $c \to ul^+l^-$ branching ratio by up to a factor of three.

3 Long distance contributions

The most serious problem with looking for new physics in charm processes is the presence of the long distance (LD) contributions in the corresponding meson decays.

The charm meson decays $D \to V\gamma$ ($V = \rho, K^*, \omega, \phi$) with the flavour structure $c\bar{q} \to u\bar{q}\gamma$ ($q = d, s$) are dominated by the LD mechanism sketched in Fig. 4, 5, 6. This disturbing LD contribution is much smaller in the case of the $b$ spectator quark due to the small $V_{cb}^*V_{ub}$. As $B_c \to B^*_u\gamma$ is the least LD contaminated decay, it has been proposed as a probe for the $c \to u\gamma$ transition [1]. Its branching ratio can reach up to $1 \times 10^{-6}$ is general MSSM [7], while the standard model prediction [8] is $1 \times 10^{-8}$. 

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The long distance mechanism \( c \bar{u} \rightarrow d\bar{d} \gamma \) (see Fig. 4(b)) overshadows the short distance process of interest \( c \bar{u} \rightarrow u \bar{u} \gamma \) in \( D^0 \rightarrow \rho^0 \gamma \) and \( D^0 \rightarrow \omega \gamma \) decays, since the final vector mesons \( \rho^0 \) and \( \omega \) are mixtures of \( u \bar{u} \) and \( d \bar{d} \) states. The LD contributions largely cancel in the difference of the decay rates

\[
R = \frac{Br[D^0 \rightarrow \omega \gamma] - Br[D^0 \rightarrow \rho^0 \gamma]}{Br[D^0 \rightarrow \omega \gamma]} \propto Re \frac{A[D^0 \rightarrow u \bar{u} \gamma]}{A[D^0 \rightarrow d \bar{d} \gamma]},
\]

which is proportional to the short distance amplitude \( A[D^0 \rightarrow u \bar{u} \gamma] \) driven by \( c \rightarrow u \gamma \). The difference of the decay rates was proposed as a probe for the \( c \rightarrow u \gamma \) transition \([10]\). The relative difference \( R \) can amount up to \( \mathcal{O}(1) \) in general MSSM, as compared to the standard model prediction of \( R = 6 \pm 15\% \) \([10]\).

| \( D^0 \rightarrow K^0 \mu^+ \mu^- \) | \( Br^{\text{theor}} \) | \( Br^{\text{exp}} \) |
|-------------------|-------------|-------------|
| \( D^0 \rightarrow K^+ l^- \) | \( 5.0 \cdot 10^{-7} \) | \( < 2.6 \cdot 10^{-4} \) |
| \( D^0 \rightarrow \pi^+ l^- \) | \( 6.2 \cdot 10^{-6} \) | \( < 1.4 \cdot 10^{-4} \) |
| \( D^0 \rightarrow \eta l^- \) | \( 3.9 \cdot 10^{-7} \) | \( < 1.8 \cdot 10^{-4} \) |
| \( D^0 \rightarrow \pi^+ l^- \) | \( 1.4 \cdot 10^{-7} \) | \( < 5.3 \cdot 10^{-4} \) |
| \( D^0 \rightarrow \pi^0 l^- \) | \( 1.7 \cdot 10^{-6} \) | \( < 7.8 \cdot 10^{-6} \) |
| \( D_s^+ \rightarrow K^+ l^- \) | \( 8.3 \cdot 10^{-8} \) | \( < 1.4 \cdot 10^{-4} \) |
| \( D^+ \rightarrow K^+ l^- \) | \( 8.2 \cdot 10^{-9} \) | \( < 8.1 \cdot 10^{-6} \) |
| \( D^0 \rightarrow K^0 l^- \) | \( 1.3 \cdot 10^{-9} \) | |

Table 1: The predicted branching ratios \( Br^{\text{theor}} \) and the experimental upper bounds \( Br^{\text{exp}} \) \([4, 8]\) for the weak charm meson decays \( D \rightarrow P \mu^+ \mu^- \), which are driven by the long distance mechanism.

Similarly, the \( c \rightarrow ul^+l^- \) transition is overshadowed by the LD contributions in the charm meson decays \( D \rightarrow Vl^+l^- \) \([3, 11]\) and \( D \rightarrow Pl^+l^- \) \( (P = \pi, K, \eta) \) \([8, 9]\). The first theoretical analysis of all \( D \rightarrow Pl^+l^- \) decays has undertaken the Heavy Meson Chiral Lagrangian approach \([8]\) with the predictions given in Table 3. The unique possibility to look for \( c \rightarrow ul^+l^- \) transition is represented by the \( D \rightarrow \pi l^+l^- \) decays in the kinematical region of \( m_{ul} \) above the resonance \( \phi \), where the long distance contribution is reduced (see Fig. 3). The kinematical region above \( \phi \) does not exist in other \( D \rightarrow XL^+l^- \) decays, since all the other mesons are heavier than the pion. Unfortunately, this kinematical region is not suitable to probe the possible enhancement of \( c \rightarrow ul^+l^- \) within general MSSM, which enhances the
rate at small $m_{ll}$ as displayed in Fig. 4. In general, the $D \to P l^+ l^-$ decays are not suitable to probe the possible enhancement of $c \to u\gamma \to ul^+ l^-$ decay via an almost real photon, since the decay $D \to P \gamma$ is forbidden for the case of the real photon.

![Figure 5: The differential branching ratio $dBr/dm_{\mu\mu}^2$ for $D^+ \to \pi^+ \mu^+ \mu^-$ decay in the standard model. The dot-dashed line denotes the short-distance contribution driven by $c \to ul^- l^-$, while the solid line denotes the long distance contribution.](image)

4 Conclusions

We have examined the $c \to u\gamma$ and $c \to ul^+ l^-$ rates in the context of the minimal supersymmetric standard model and proposed the relevant hadronic observables, which are relatively free of the long distance contributions.

Schemes with universal soft breaking terms have negligible effect on these processes. If the universality condition is relaxed, the dominant contribution comes from the gluino exchange diagrams with the left-right squark mass insertion. The $c \to u\gamma$ rate can be enhanced up to $6 \times 10^{-6}$, compared to the QCD corrected standard model prediction $3 \times 10^{-8}$. The supersymmetric effect is sizable at small di-lepton masses in the case of the $c \to ul^+ l^-$ decay and can enhance its rate by at most a factor of three.

The supersymmetric enhancement of the $c \to u\gamma$ rate can be probed in the $B_c \to B^{*\gamma}_u$ decay [9] at LHC, which is expected to produce $2 \times 10^8 B_c$ mesons with $p_T > 20$ GeV. Another possibility is represented by the difference of the decays rates $D^0 \to \rho^0 \gamma$ and $D^0 \to \omega \gamma$ [10], which could be explored at BaBar, Belle, BTeV and possibly tau-charm factory. The $c \to ul^+ l^-$ transition is overshadowed by the long distance contributions to rare di-lepton charmed meson decays and we present the predictions for their rates in Table 4.
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