Probing the unparticle signal in $b \rightarrow d$ penguin processes

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Abstract

We investigate the effect of unparticles in the pure $b \rightarrow d$ penguin processes $B^0 \rightarrow K^0 \bar{K}^0$ and $B^{+,0} \rightarrow \phi \pi^{+,0}$. Since these processes receive dominant contributions due to the top quark in the loop, direct and mixing-induced CP asymmetry parameters in these processes are expected to be vanishingly small in the standard model. We find that due to the unparticle effect sizable nonzero CP violation could be possible in these channels.

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The standard model (SM) of electroweak interaction is very successful in explaining the observed data so far (with the exception of neutrinos), but still it is believed that the SM is not the complete theory but rather a low energy manifestation of a higher theory, the form which is yet unknown. There exist many beyond the SM scenarios with interesting consequences which are being tested at present or are likely to be tested in the future experiments. In this context, it is expected that the SM predictions will be subjected to intense scrutiny in the upcoming experiments at the LHC or ILC to decipher the existence of new physics, if any. The study of B physics provides us an opportunity to test the SM predictions and to look for physics beyond the SM.

Recently a very promising idea has been proposed by Georgi [1] which could in principle exist and might have been undetected so far. The possible signatures of it may be found at the upcoming experiments such as the LHC. This fascinating idea, called unparticle physics, has already taken the center stage and is believed to be one of the viable new physics scenarios.

In the context of conventional particle physics the scale invariance is broken which is very well described by the Quantum Field Theory with most of the particles having definite mass. But there could be a hidden theory which is scale invariant, with a non-trivial infrared fixed point, whose fields are known as Banks-Zaks (BZ) fields [2]. It is further assumed that the scale invariant theory interacts very weakly with that of SM particles by the exchange of very massive particles with the generic form $O_{SM}O_{BZ}/M_{U}^{k}$. The renormalizable couplings of the BZ fields induce dimensional transmutation at some scale $\Lambda_{U}$ where the scale invariance appears. Below this scale the BZ operators match onto corresponding unparticle operators leading to a new set of interactions

$$C_{U} \frac{\Lambda_{U}^{d_{BZ}-d_{U}}}{M_{U}^{k}} O_{SM}O_{U},$$

where $C_{U}$ is a coefficient in the low energy effective theory and $O_{U}$ is the unparticle operator with scaling dimension $d_{U}$. Furthermore, $M_{U}$ should be large enough such that its coupling to the SM must be sufficiently weak, consistent with the current experimental data. It is this feebleness of the interaction for which the unparticle sector might have been undetected so far. Interestingly, the unparticle stuff with a scale dimension $d_{U}$ looks like non-integral number $d_{U}$ of invisible massless particles. The effect of unparticle stuff on low energy phenomenology has been extensively explored in Ref. [3].
A clean signal of the unparticle stuff can be inferred from various analyses, e.g., the missing energy distribution in mono-photon production via $e^-e^+ \rightarrow \gamma U$ at LEP2 and direct CP violation in the pure leptonic $B^{\pm} \rightarrow l^\pm \nu_l$ modes etc. In this paper we would like to investigate the effect of unparticle stuff in the rare decay modes $B^{\pm,0} \rightarrow \phi \pi^{\pm,0}$ and $B^0 \rightarrow K^0 \bar{K}^0$, which have only $b \rightarrow d$ penguin contributions in the standard model. These processes are highly suppressed in the SM, as they arise only at the loop level, involving the CKM matrix element combinations $V_{qb}V_{qd}^*$ with $q = u, c, t$, which are very small i.e., $\mathcal{O}(\lambda^3)$ in the Wolfenstein parameterization, and thus provide an excellent testing ground for new physics. Therefore, it is natural to expect that the effect of unparticle stuff, if it exists, could show up, with striking signals in these channels.

In order to see the effect of unparticles in these channels let us first briefly describe the various observables, which will be measured in the upcoming LHCb experiments. The time dependent CP asymmetry for $B^0 \rightarrow f$, where the final state $f$ stands for $\phi \pi^0/K^0 \bar{K}^0$ which could be accessible from both $B^0$ and $\bar{B}^0$, can be given by

$$a_{CP}(t) = \frac{\Gamma(\bar{B}^0_d(t) \rightarrow f) - \Gamma(B^0_d(t) \rightarrow f)}{\Gamma(\bar{B}^0_d(t) \rightarrow f) + \Gamma(B^0_d(t) \rightarrow f)} = S_f \sin \Delta m_{B_d} t - C_f \cos \Delta m_{B_d} t,$$

where

$$S_f = \frac{2 \text{Im}(\lambda)}{1 + |\lambda|^2}, \quad C_f = \frac{1 - |\lambda|^2}{1 + |\lambda|^2},$$

are the mixing-induced and direct CP violating parameters. In the above expression $\lambda$ corresponds to

$$\lambda = \frac{q A(\bar{B}^0_d \rightarrow f)}{p A(B^0_d \rightarrow f)},$$

where $q$ and $p$ are the mixing parameters, represented by the CKM elements in the SM as

$$\frac{q}{p} = \frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*} \sim e^{-2i\beta}.$$ 

Since in the SM the decay mode $B^0_d \rightarrow \phi \pi^0 (K^0 \bar{K}^0)$ receives dominant contribution only from $b \rightarrow d$ penguins with top quark in the loop, one can generically write the decay amplitude as

$$A(\bar{B}^0_d \rightarrow f) = \frac{G_F}{\sqrt{2}} V_{tb} V_{td}^* P_t,$$

where $V_{ij}$ are the CKM matrix elements which provide the weak phase information and $P_t$ is the penguin amplitude arising from the matrix elements of the four quark operators of the
effective Hamiltonian. The amplitude for the corresponding CP conjugate process is given as
\[ A(B_d^0 \to f) = -\frac{G_F}{\sqrt{2}} V_{tb}^* V_{td} P_t . \] (6)
So we have
\[ \lambda = \left( \frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*} \right) = 1 , \] (7)
and hence
\[ C_f = S_f = 0 . \] (8)
Thus, if the measured CP violating asymmetries in \( B^0 \to \phi \pi(K^0 \bar{K}^0) \) deviate significantly from zero then it would be a clear signal of new physics. Moreover, the decay amplitude also receives some contribution from the internal up and charm quarks in the loop. Therefore, the CP violating parameters will not be identically zero but will have small nonzero values. However, including these contributions it is shown in Ref [4] that the CP violating observables in the decay mode \( B^0 \to K^0 \bar{K}^0 \) is rather small in the SM. Hence, in this analysis we will assume that the standard model amplitude to be dominated by the top quark penguin.

Now, we will include the new contributions to the decay amplitudes arising due to the unparticle stuff. It should be noted that, depending on the nature of the original BZ operator \( O_{BZ} \) and the transmutation, the resulting unparticle may have different Lorentz structures. In our analysis, we consider only the vector type unparticle exchange. Under the scenario that the unparticle stuff transforms as a singlet under the SM gauge group \([1]\), the unparticles can couple to different flavors of quarks and induce flavor changing neutral current (FCNC) transitions even at the tree level. Thus, the coupling of the vector-type unparticles \( (O_{Ut}^\mu) \) to quarks is given as
\[ \frac{c_{V}^{q'q}}{\Lambda_{Ut}^{d_{Ut}-1}} q' \gamma_\mu (1 - \gamma_5) q \ O_{Ut}^\mu + h.c. , \] (9)
where \( c_{V}^{q'q} \) are the dimensionless coefficients which in general depend on different flavors. If both \( q \) and \( q' \) belong to up (down) quark sector, FCNC transitions can be induced by the above effective interactions. We will consider these couplings to be real so that the CP odd weak phase associated with the unparticle couplings is zero. The propagator for the vector unparticle is given by
\[ \int d^4x e^{iP \cdot x} \langle 0 | T O_{Ut}^\mu(x) O_{Ut}^\nu(0) | 0 \rangle = i \frac{A_{Ut}}{2 \sin \theta_{Ut}} \frac{-g_{\mu\nu} + P_{\mu} P_{\nu}/P^2}{(P^2)^{2-d_{Ut}}} e^{-i\phi_{Ut}} . \] (10)
where
\[
A_{du} = \frac{16\pi^{5/2}}{(2\pi)^{2dU}} \frac{\Gamma(d_U + 1/2)}{\Gamma(d_U - 1)\Gamma(2d_U)} , \quad \text{and} \quad \phi_U = (d_U - 2)\pi .
\] (11)

After knowing the nature of interactions between the unparticles and the quarks, we are now interested to see how they will affect the transition amplitudes for the processes under consideration. Due to the effect of vector like unparticle, the new contributions to the \(B_d^0 \to \phi\pi(K^0\bar{K}^0)\) decay amplitudes are given as
\[
A(\nu^0 \to \phi\pi(K^0\bar{K}^0)) = -e^{-i\phi_U} \frac{2}{P^2} \frac{A_{du}}{2\sin d_U\pi} \left(\frac{P^2}{\Lambda_{du}^2}\right)^{d_U-1} X ,
\] (12)
where \(X = \langle \phi\pi(K^0\bar{K}^0) | (V - A)_\mu (V - A)_\mu | B^0 \rangle\) is the hadronic matrix element. In the above equation we have taken the momentum transferred to the unparticle as \(P^2 = m_{Bd}\Lambda\) with \(\Lambda = m_{Bd} - m_b\).

Now, including the unparticle contributions, one can write the total amplitude as
\[
A^T(B_d^0 \to f) = A_{SM} (1 + r e^{i(\beta - \phi_U)}) ,
\] (13)
where \(A_{SM}\) is the SM amplitude as given in (6), \(\beta\) is the weak phase associated with the CKM elements \(V_{tb}V^*_{td}\), \(\phi_U\) is the CP conserving strong phase associated with the time-like unparticle propagator and \(r\) denotes the ratio of unparticle to SM amplitude, which is given as
\[
r = \frac{2}{G_F P^2} \frac{1}{\sqrt{2} \sin (d_U\pi)} \frac{A_{du}}{(\Lambda_{du}^2)} \left(\frac{P^2}{\Lambda_{du}^2}\right)^{d_U-1} X .
\] (14)

Thus, we obtain the CP averaged branching ratio \(\langle \text{Br} \rangle \equiv [\text{Br}(B_d^0 \to f) + \text{Br}(\bar{B}_d^0 \to f)]/2\), including the unparticle contributions, as
\[
\langle \text{Br} \rangle = \text{Br}_{SM} (1 + r^2 + 2r \cos \beta \cos \phi_U) ,
\] (15)
where \(\text{Br}_{SM}\) is the SM branching ratio. The expressions for the CP asymmetries become
\[
S_f = -\frac{2r \cos \phi_U \sin \beta + r^2 \sin 2\beta}{1 + r^2 + 2r \cos \phi_U \cos \beta} ,
\] (16)
\[
C_f = \frac{2r \sin \phi_U \sin \beta}{1 + r^2 + 2r \cos \phi_U \cos \beta} .
\] (17)

Thus, one can see that the branching ratio and the CP violating observables crucially depend on the value of \(r\) which in fact contains several unknown parameters i.e., the dimension of the unparticle fields \(d_U\), the energy scale \(\Lambda_{du}\) and the couplings \(c^{\nu}_V, c^{\nu^*}_V\). Therefore, it is not
possible to constrain the new physics contributions unless we fix some of these parameters. The coupling constants $c_{db}^{V}$ can be constrained by the $B^0 - \bar{B}^0$ mixing data. Due to the unparticle exchange, the mass difference can be explicitly given as

$$\Delta m_{B_d} = \frac{1}{2} \frac{f_{B_d}^2 \hat{B}_{B_d}}{m_{B_d}} \frac{A_{dU}}{2|\sin d_{U\pi}|} \left( \frac{m_{B_d}}{\Lambda_{U}} \right)^{2d_{U}-2} |c_{V}^{db}|^2.$$  \hspace{1cm} (18)

Assuming that the total contributions is given by the unparticles and using the result of $\Delta m_{B_d} = 0.507$ ps$^{-1}$, $f_{B_d} \sqrt{\hat{B}_{B_d}}=0.2$ GeV, the energy scale $\Lambda_{U}=1$ TeV and the scale dimension $d_{U}=3/2$, one can obtain the upper bound on $c_{V}^{db}$ as

$$|c_{V}^{db}| \leq 2.3 \times 10^{-4}.$$  \hspace{1cm} (19)

However, the variation of the coupling $c_{V}^{db}$ with the scale dimension $d_{U}$ for $\Lambda_{U}=1$ TeV, is shown in figure-1.

![FIG. 1: Variation of $c_{V}^{db}$ with $d_{U}$.

Now let us first consider the decay mode $B^0 \rightarrow K^0 \bar{K}^0$. The CP averaged branching ratio for this mode has already been measured with value $\ [6]$ 

$$\text{Br}(B^0 \rightarrow K^0 \bar{K}^0) = (0.96^{+0.21}_{-0.16}) \times 10^{-6},$$ \hspace{1cm} (20)

which agrees with the SM predictions $\ [7]$. The CP violating parameters are recently measured by both Babar $\ [8]$ and Belle $\ [9]$ collaborations and the world average values are

$$\langle S_{KK} \rangle = -0.82 \pm 0.55, \quad \langle C_{KK} \rangle = 0.02 \pm 0.28.$$ \hspace{1cm} (21)

Although, the measured branching ratio and the CP violation parameters (with large error bars) do not provide any clear indication for a possible new physics effect, the precise
measurements of CP violation parameters in near future will certainly establish/rule out the presence of new physics in this channel.

The standard model amplitude for this process is given as

$$A(\bar{B}_d^0 \to K^0\bar{K}^0) = -\frac{G_F}{\sqrt{2}} V_{tb} V_{td}^* \left[ a_4 - \frac{a_{10}}{2} + r_X \left( a_6 - \frac{a_8}{2} \right) \right] X,$$  \hspace{1cm} (22)

where $r_X = \frac{2m_K^2}{(m_b - m_s)(m_s + m_d)} \approx 0.85$ is the chiral enhancement factor and $X$ is the factorized matrix element given as

$$X = \langle K^0|\bar{s}\gamma_\mu(1-\gamma_5)b|\bar{B}_d^0\rangle \langle K^0|\bar{d}\gamma_\mu(1-\gamma_5)s|0\rangle = -if_K F_0(m_K^2) (m_B^2 - m_K^2).$$  \hspace{1cm} (23)

Now using the QCD coefficients $a_i$'s from [10], the value of the form factor $F_0(m_K^2)$ obtained using light cone QCD sum rule approach [11], the particle masses, lifetime of $B^0$ and $K$ meson decay constant $f_K = 0.16$ GeV taken from [3], the CKM matrix elements as $|V_{tb}| = 0.999125$, $|V_{td}| = 8.72 \cdot 10^{-3}$ [12], we obtain the CP averaged branching ratio as

$$\text{Br}(B^0 \to K^0\bar{K}^0) = 8.6 \times 10^{-7}. \hspace{1cm} (24)$$

Although the predicted branching ratio is in agreement with the experimental value, the presence of new physics in this channel is not completely ruled out unless the CP violating parameters are measured precisely, in conformity with the SM expectations.

Now including the contributions arising from unparticle stuff we show the variation of the CP averaged branching ratio (15), with the scale dimension $d_U$ in figure-2, where we have used the energy scale $\Lambda_{d_U}=1$ TeV, the value of $c_{U}^{db}$ for different $d_U$ is extracted from the $B^0 - \bar{B}^0$ mixing data (as shown in Figure-1), some representative set of values for $c_{U}^{ss}$ and the weak phase $\beta = 0.385$ rad. From the figure one can see that the observed branching ratio can be explained with unparticle physics for $d_U > 1.2$. As $d_U$ increases the branching ratio tends to the corresponding SM value.

The direct and mixing induced CP asymmetries are shown in Figure-3, where it is found that significant CP asymmetry could be possible due to unparticle effect. As can be seen, large CP asymmetry is possible for large $c_{U}^{ss}$. And as $d_U$ increases these parameters tend to the corresponding SM values.

Next we consider the processes $B^{+,0} \to \phi\pi^{+,0}$. These modes have another interesting feature that they receive dominant contribution from electroweak penguins as the strong penguins are OZI suppressed. Hence they also provide an ideal testing ground to look for
FIG. 2: CP averaged branching ratio \(\langle \text{Br} \rangle\) (in units of \(10^{-6}\)) for the decay mode \(B^0 \rightarrow K^0 \bar{K}^0\), where the solid, dashed and dot-dashed lines correspond to \(c_{V^s} = 0.05, 0.01\) and \(0.005\) respectively. The horizontal thick lines represent the range of the experimental data.

FIG. 3: Direct (in %) and mixing induced CP violation parameters for the decay mode \(B^0 \rightarrow K^0 \bar{K}^0\), where the solid, dashed and dot-dashed lines correspond to \(c_{V^s} = 0.05, 0.01\) and \(0.005\) respectively.

NP. These modes have been analyzed in various beyond the SM scenarios in Ref. [13]. At present only the upper limits of their branching ratios are known [6]:

\[
\begin{align*}
\text{Br}(B^+ \rightarrow \phi \pi^+) &< 0.24 \times 10^{-6} , \\
\text{Br}(B^0 \rightarrow \phi \pi^0) &< 0.28 \times 10^{-6} .
\end{align*}
\]

(25)

Let us first concentrate on \(B^+ \rightarrow \phi \pi^+\) process. In the SM, it receives contribution from the quark level transition \(b \rightarrow d \bar{s}s\), which is induced by the pure penguin diagram with dominant contributions coming from electroweak penguins. Using the generalized factorization
approach one can write the transition amplitude as

\[ A^{SM}(B^+ \rightarrow \phi \pi^+) = -\frac{G_F}{\sqrt{2}} V_{tb} V_{td} \left[ a_3 + a_5 - \frac{1}{2} (a_7 + a_9) \right] X, \quad (26) \]

where

\[ X = \langle \pi^+(p_\pi) | \bar{d} \gamma_\mu (1 - \gamma_5) b | B^+(p_B) \rangle \langle \phi(q, \epsilon) | \bar{s} \gamma^\mu (1 - \gamma_5) s | 0 \rangle \]

\[ = 2 F_{B \rightarrow \pi}(m_\phi^2) f_\phi m_\phi (\epsilon \cdot p_B). \quad (27) \]

is the factorized matrix element. The amplitude for \( B^0 \rightarrow \phi \pi^0 \) is related to \( B^+ \rightarrow \phi \pi^+ \) by

\[ A(B^0 \rightarrow \phi \pi^0) = A(B^+ \rightarrow \phi \pi^+)/\sqrt{2}. \]

The branching ratio can be obtained using the formula

\[ \text{BR}(B^+ \rightarrow \phi \pi^+) = \frac{\tau_{B^+}}{8 \pi m_\phi^3} |A(B^+ \rightarrow \phi \pi^+)/\epsilon \cdot p_B|^2, \]

\[ \text{BR}(B^0 \rightarrow \phi \pi^0) = \frac{\kappa}{2} \text{BR}(B^+ \rightarrow \phi \pi^+), \quad (28) \]

where \( \kappa = \tau_{B^0}/\tau_{B^-} \) and \( p_{cm} \) is the momentum of the outgoing particles in the \( B \) meson rest frame.

For numerical evaluation we use the \( \phi \) meson decay constant as \( f_\phi = 0.237 \text{ GeV} \), the form factor \( F_{B \rightarrow \pi}(\phi^2) \) is obtained using QCD sum rule approach and the other parameters as presented for \( B \rightarrow KK \) mode. Thus, we obtain the branching ratio for \( B^{+,0} \rightarrow \phi \pi^{+,0} \) in the SM as

\[ \text{Br}(B^+ \rightarrow \phi \pi^+) = 3.95 \times 10^{-9}, \]

\[ \text{Br}(B^0 \rightarrow \phi \pi^0) = 1.85 \times 10^{-9}. \quad (29) \]

These predicted values are quite below the present experimental upper limits.

Now including the unparticle contributions, the branching ratio and the direct CP asymmetry parameters for the \( B^+ \rightarrow \phi \pi^+ \) are plotted in Fig-4. From the figure one can see that the branching ratio can be enhanced significantly and also large direct CP violation could be possible in this channel. Since the direct CP violation in the SM is identically zero, the observation of nonzero CP violation in this channel could be a direct signal of NP and the unparticle stuff will be a strong contender of it.

One of the important goals of the B-factory is to verify the standard model predictions and to serve as a potential avenue to reveal new physics beyond the standard model (BSM). Among the various BSM scenarios the recently advocated unparticle physics scenario looks
FIG. 4: CP averaged branching ratio $\langle \text{Br} \rangle$ (in units of $10^{-8}$) and direct CP violation parameter (in %) for the decay mode $B^+ \to \phi\pi^+$, where the solid, dashed and dot-dashed lines correspond to $c_{V^s} = 0.05$, 0.01 and 0.005 respectively.

like a very strong candidate indeed. In this context many interesting and novel consequences have been pointed out in the literature which are likely to be tested in the future experiments. In this paper, we have explored some rare $b \to d$ penguin decay modes (namely, $B^0 \to K^0\bar{K}^0$ and $B \to \phi\pi$) to study the effect of unparticle physics and possible signatures of it. Specifically, in the case of $B^0 \to K^0\bar{K}^0$ mode although the branching ratio appears to be in agreement with the SM expectation but CP violating parameters can reveal the existence of NP. It should be noted that the CP violating parameters are close to zero in the SM and nonzero values of the same, if found, will clearly signal NP. Here we found that significant nonzero CP asymmetry can be expected if unparticle effect is taken into account. Similarly, in the case of $B \to \phi\pi$ modes the branching ratios are very small (only upper limits have been obtained so far) and the contribution due to the unparticles can enhance the branching ratios to significant ones. The direct CP violation in $B^+ \to \phi\pi^+$ is also zero in the SM but because of the unparticles we can expect large direct CP violation in this case. To conclude, we have presented here some rare decay modes where the SM predictions can be altered significantly by the inclusion of unparticle effect which may be tested in the upcoming experiments.
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