Possible signatures of unparticles in rare annihilation type B decays

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(Received 24 July 2007; published 27 September 2007)

We investigate the effect of unparticles in the pure annihilation type decays $B^- \to D_s^- \phi$ and $D_s^- K^{*0}$. Since these decays have only annihilation contributions their branching ratios are expected to be very small in the standard model and the direct CP asymmetry parameters to be zero. We find that due to the unparticle effect these branching ratios can be significantly enhanced from their standard model values. Furthermore, sizable nonzero direct CP violation could also be possible in these channels due to the presence of intrinsic CP conserving phase in the unparticle propagator.

DOI: 10.1103/PhysRevD.76.057701 PACS numbers: 14.80.−j, 11.30.Er, 13.25.Hw

There are many discrete massive particles in reality which can exist in a scale noninvariant theory as in the case of the standard model (SM) whereas, in a scale invariant theory, in four space-time dimensions, the mass spectrum of fields is continuous or zero. Recently, Georgi [1] suggested that there could be a possibility that the scale invariant sector (termed as unparticle) indeed exists but might have been undetected so far as the intermediate particles mediating these two sectors are believed to be very heavy. The standard model fields might be scale invariant at high energy but scale invariance might have been broken somewhere above the electroweak scale. However, here the SM is taken to be scale noninvariant all the way up to high energy.

Now let us consider a scenario in which there exists the scale invariant sector with nontrivial infrared fixed point at high energy, which is represented by the Banks-Zaks (BZ) fields [2], and also the SM fields. Thus, the high energy theory contains both the SM fields and the BZ fields, which interact via the exchange of particles of mass $M_{\mathcal{U}}$ with the generic form

$$\frac{1}{M_{\mathcal{U}}^k} O_{\rm SM} O_{\rm BZ},$$

where $O_{\rm SM}$ is the operator of mass dimension $d_{\rm SM}$ and $O_{\rm BZ}$ is the operator of mass dimension $d_{\rm BZ}$ made out of SM and BZ fields, respectively. The couplings of the BZ fields cause dimensional transmutation and below the scale $\Lambda_{\mathcal{U}}$ the BZ operators match onto the unparticle operators leading to the interaction between the SM and the unparticle sector of the type

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

where $C_{\mathcal{U}}$ is a coefficient in the low energy effective theory and $O_{\mathcal{U}}$ is the unparticle operator with scaling dimension $d_{\mathcal{U}}$. Furthermore, $M_{\mathcal{U}}$ should be large enough such that its coupling to the SM fields must be sufficiently weak, consistent with the current experimental data.

Unparticle stuff with scale dimension $d_{\mathcal{U}}$ looks like a nonintegral number $d_{\mathcal{U}}$ of invisible massless particles. Unparticle, if it exists, could couple to the standard model fields and consequently affect the low energy dynamics. The effect of unparticle stuff on low energy phenomenology has been extensively explored in Refs. [3–6].

A clean signal of the unparticle stuff can be inferred from various analyses, e.g., the missing energy distribution in monophoton production via $e^- e^+ \to \gamma \mathcal{U}$ at LEP2 [3] and direct CP violation in the pure leptonic $B^\pm \to l^\pm \nu_l$ modes, etc. [5,6]. In this paper, we would like to see whether the pure annihilation type B decays could provide any interesting avenues to visualize the signatures of unparticles. The decay modes considered here are $B^- \to D_s^- \phi$ and $D_s^- K^{*0}$ which have only annihilation type contributions in the SM and are therefore expected to be very rare. Only the upper limits are known for these channels which are given as ${\rm Br}(B^+ \to D_s^+ \phi) < 1.9 \times 10^{-6}$ and ${\rm Br}(B^+ \to D_s^+ \bar{K}^{*0}) < 4 \times 10^{-4}$ [7]. Furthermore, since the decay amplitudes of these modes have contributions arising only from annihilation diagrams, the direct CP asymmetry parameters in these modes are identically zero. Some new physics (NP) models like two Higgs doublet model and R-parity violating supersymmetric model can provide new contributions to these channels and thereby open up the possibility of observing direct CP violation [8]. But, if the strong phases in the SM and NP amplitudes turn out to be tiny, CP violation cannot be observed even if there is new physics contribution to the decay amplitudes. However, if the new contributions to the decay amplitudes are due to the unparticles, which contain the new CP conserving phase coming from the unparticle propagators, CP violation could be observed even for vanishing SM strong phase. In this paper we would like to explore such a possibility.

The decay modes considered here are $B^- \to D_s^- \phi$ and $D_s^- K^{*0}$ which arise in the standard model from the tree level annihilation diagrams. The b and $\bar{u}$ quarks of the initial B meson annihilate to a W^- boson which subsequently hadronizes to the final D_s^- and $\phi (K^{*0})$ mesons.

The effective Hamiltonian describing such transitions is given as

$$\mathcal{H}_{\rm eff} = \frac{G_F}{\sqrt{2}} V_{ub} V_{cq}^* [C_1(\mu) \bar{q}_\alpha \gamma_\mu (1-\gamma_5) c_\alpha \bar{u}_\beta \gamma^\mu (1-\gamma_5) \times b_\beta + C_2(\mu) \bar{q}_\beta \gamma_\mu (1-\gamma_5) c_\alpha \bar{u}_\alpha \gamma^\mu (1-\gamma_5) b_\beta], \tag{1}$$

where $C_{1,2}$ are the Wilson coefficients, α and β are the color indices, $q = s(d)$ for the final state meson $\phi(K^{*0})$. Thus one can obtain the transition amplitude for these processes as

$$A(B^-(p_B) \to D_s^-(p_D) V(p_V, \epsilon)) = \frac{G_F}{\sqrt{2}} V_{ub} V_{cq}^* a_1 X, \tag{2}$$

where V denotes the final vector meson ϕ/K^{*0}, $a_1 = C_1 + C_2/N_c$, and $X = \langle D_s^- V | \bar{q} \gamma^\mu (1-\gamma_5) c \bar{u} \gamma_\mu (1-\gamma_5) b | B^- \rangle$ is the matrix element of the four quark current operators between the initial and final mesons. The evaluation of this hadronic matrix element is not possible from the first principles of QCD and one requires some additional assumptions to determine it. Since, in this paper, we are interested to see the effect of unparticles in the CP violation asymmetries, we will not pay much attention for its evaluation. However, if one resorts to the generalized factorization approach then one can factorize this matrix element as $X = \langle D_s V | (\bar{q}c)_{V-A} (\bar{u}b)_{V-A} | B^- \rangle \equiv \langle D_s V | (\bar{q}c)_{V-A} | 0 \rangle \langle 0 | (\bar{u}b)_{V-A} | B^- \rangle$. The first element can be related to its corresponding crossed channel as $\langle D_s(p_D) V(p_V, \epsilon) | (\bar{q}c)_{V-A} | 0 \rangle \equiv \langle V(p_V, \epsilon) | (\bar{q}c)_{V-A} | D_s(-p_D) \rangle$. Using Lorentz invariance, these matrix elements can be represented in terms of form factors and decay constants, as defined in [9]. Thus one can obtain the transition amplitude as

$$A(B^-(p_B) \to D_s^-(p_D) V(p_V, \epsilon)) = -\frac{G_F}{\sqrt{2}} V_{ub} V_{cq}^* a_1 f_B 2 m_V (\epsilon^* \cdot p_D) A_0(p_B^2). \tag{3}$$

The corresponding branching ratio is given as

$$\mathrm{Br}(B^- \to D_s^- V) = \frac{p_c^3}{8\pi m_V^2} |A(B^- \to D_s V)/(\epsilon^* \cdot p_D)|^2, \tag{4}$$

where p_c is the c.m. momentum of the emitted particles in the B rest frame.

Now we would like to see how unparticle stuff will affect the transition amplitudes. Here, we assume that the charged unparticles mediate the interaction between the initial and final mesons. The possible existence of charged unparticles and their consequences have been recently discussed in Refs. [5,6]. It is well known that, depending on the nature of the original BZ operator $O_{\rm BZ}$ and the transmutation, the resulting unparticle may have different Lorentz structure. In our analysis, we consider only the scalar and vector type unparticles. The coupling of these unparticles to quarks is given as

$$\frac{c_S^{q'q}}{\Lambda_{\mathcal{U}}^{d_\mathcal{U}}} \bar{q}' \gamma_\mu (1-\gamma_5) q \partial^\mu O_\mathcal{U} + \frac{c_V^{q'q}}{\Lambda_{\mathcal{U}}^{d_\mathcal{U}-1}} \bar{q}' \gamma_\mu (1-\gamma_5) q O_\mathcal{U}^\mu + \mathrm{H.c.}, \tag{5}$$

where $O_\mathcal{U}$ and $O_\mathcal{U}^\mu$ denote the scalar and vector unparticle fields and $c_{S,V}^{q'q}$ are the dimensionless coefficients which in general depend on different flavors and are assumed to be real. For the charged unparticle exchange, q' in Eq. (5) belongs to the up quark sector (u, c, t) and q to the down-type quarks (d, s, b).

The propagator for the scalar unparticle field is given as [1,3]

$$\int d^4x e^{iP\cdot x} \langle 0 | T O_\mathcal{U}(x) O_\mathcal{U}(0) | 0 \rangle = i \frac{A_{d_\mathcal{U}}}{2 \sin d_\mathcal{U} \pi} \frac{1}{(P^2 + i\epsilon)^{2-d_\mathcal{U}}} e^{-i\phi_\mathcal{U}}, \tag{6}$$

where

$$A_{d_\mathcal{U}} = \frac{16\pi^{5/2}}{(2\pi)^{2d_\mathcal{U}}} \frac{\Gamma(d_\mathcal{U} + 1/2)}{\Gamma(d_\mathcal{U} - 1)\Gamma(2d_\mathcal{U})} \quad \text{and} \quad \phi_\mathcal{U} = (d_\mathcal{U} - 2)\pi. \tag{7}$$

Similarly, the propagator for the vector unparticle is given by

$$\int d^4x e^{iP\cdot x} \langle 0 | T O_\mathcal{U}^\mu(x) O_\mathcal{U}^\nu(0) | 0 \rangle = i \frac{A_{d_\mathcal{U}}}{2 \sin d_\mathcal{U} \pi} \frac{-g^{\mu\nu} + P^\mu P^\nu / P^2}{(P^2 + i\epsilon)^{2-d_\mathcal{U}}} e^{-i\phi_\mathcal{U}}. \tag{8}$$

The interesting thing in these propagators is the presence of the new CP conserving phase $\phi_\mathcal{U}$, which leads to a spectacular interference pattern and hence can exhibit nonzero direct CP violating effects in many rare decay channels. Here it should be noted that the vector unparticle will not contribute to the decay channels considered here. This is because the contraction of P_μ arising from axial coupling, i.e., $\langle 0 | A_\mu | B^- \rangle$ with the $(-g^{\mu\nu} + P^\mu P^\nu / P^2)$ term in the vector unparticle propagator gives vanishing contribution, while the vector coupling $\langle 0 | V_\mu | B^- \rangle$ is identically zero. Therefore, only scalar-type unparticles will contribute to these rare decay modes. Thus, the contributions arising from scalar unparticle exchange is given as

$$A^\mathcal{U}(B^- \to D_s^- V) = \frac{\lambda}{\Lambda_\mathcal{U}^{2d_\mathcal{U}}} \frac{A_{d_\mathcal{U}}}{2 \sin(d_\mathcal{U} \pi)} (m_B^2)^{d_\mathcal{U} - 1} e^{-i\phi_\mathcal{U}} X, \tag{9}$$

where $\lambda = (c_S^{ub} c_S^{cq})$ and X is the hadronic matrix element. Now, including the unparticle contributions, one can write the transition amplitude as

$$A^T(B^-(p_B) \to D_s^-(p_D)V(p_V, \epsilon)) = A^{\rm SM}(1 + re^{i(\gamma - \phi_{\mathcal{U}})}), \tag{10}$$

where γ is the weak phase of SM amplitude; i.e., we have used $V_{ub} = |V_{ub}|e^{-i\gamma}$. Furthermore, r denotes the magnitude of the ratio of unparticle to SM amplitude and is given as

$$r = \frac{\lambda}{\Lambda_{\mathcal{U}}^{2d_{\mathcal{U}}}} \frac{A_{d_{\mathcal{U}}}}{\sqrt{2}\sin(d_{\mathcal{U}}\pi)} \frac{(m_B^2)^{d_{\mathcal{U}}-1}}{G_F|V_{ub}V_{cq}^*|a_1}. \tag{11}$$

Thus, we obtain the CP averaged branching ratio $\langle {\rm Br}\rangle \equiv [{\rm Br}(B^- \to D_s^- V) + {\rm Br}(B^+ \to D_s^+ V)]/2$, including the unparticle contributions, as

$$\langle {\rm Br}\rangle = {\rm Br}^{\rm SM}(1 + r^2 + 2r\cos\gamma\cos\phi_{\mathcal{U}}), \tag{12}$$

where ${\rm Br}^{\rm SM}$ is the SM branching ratio. It should be noted that since the direct CP violation in these modes is zero in the SM, the SM CP averaged branching ratio is the same as ${\rm Br}(B^- \to D_s^- V)$. The direct CP violation parameter, which is related to the difference of the partial decay rates, is given as

$$A_{CP} = \frac{\Gamma(B^- \to D_s^- V) - \Gamma(B^+ \to D_s^+ \bar{V})}{\Gamma(B^- \to D_s^- V) + \Gamma(B^+ \to D_s^+ \bar{V})} = \frac{2r\sin\gamma\sin\phi_{\mathcal{U}}}{1 + r^2 + 2r\cos\gamma\cos\phi_{\mathcal{U}}}. \tag{13}$$

We now proceed to evaluate the SM branching ratios using the QCD factorization approach. Although the QCD factorization predictions for annihilation contributions suffer from end point divergences, and therefore have large uncertainties, one can still have an estimate on the order of the branching ratios. In this approach, the annihilation amplitudes are parametrized as [10]

$$A(B^- \to D_s^- V) = i\frac{G_F}{\sqrt{2}} V_{ub}V_{cq}^* f_B f_{D_s} f_V b_2(D_s, V), \tag{14}$$

where $b_2 = C_F C_2 A_1^i/N_c^2$, with $C_F = 4/3$ as the color factor and N_c is the number of colors. A_1^i is given as

$$A_1^i \approx 6\pi\alpha_s\left[3\left(X_A - 4 + \frac{\pi^2}{3}\right) + r_\chi^{D_s} r_\chi^V (X_A^2 - 2X_A)\right], \tag{15}$$

where

$$r_\chi^{D_s} = \frac{2m_{D_s}^2}{m_b(m_c + m_s)}, \qquad r_\chi^V = \frac{2m_V}{m_b}\frac{f_V^\perp}{f_V}. \tag{16}$$

X_A denotes the end point divergences which can be parametrized as

$$X_A = (1 + \rho_A e^{i\phi_A})\ln\left(\frac{m_B}{\Lambda_h}\right) \quad \text{with} \quad \Lambda_h = 0.5~\text{GeV}. \tag{17}$$

For the numerical evaluation, we use the particle masses, lifetime of B^- meson, and the Cabibbo-Kobayashi-Maskawa (CKM) elements $V_{ub} = (3.96 \pm 0.09) \times 10^{-3}$, $V_{cs} = 0.972\,96 \pm 0.000\,24$, $V_{cd} = 0.2271 \pm 0.0010$ from [7]. The decay constants (in GeV) as $f_{D_s} = 0.294$ [7], $f_\phi = 0.237$ [11], $f_B = 0.2$, $f_{K^*} = 0.218$, $f_V^\perp = 0.175$ [10], the current quark masses (in GeV) as $m_b = 4.2$, $m_c = 1.3$, $m_s = 0.08$ [10]. We use $C_2 = -0.295$ [12] evaluated at $m_b/2$ scale at next-to-leading order, $\rho_A = 1$, and $\phi_A = -20°$ [10] for the annihilation parameters. Thus we obtain the branching ratios as

$$\begin{aligned} {\rm Br}^{\rm SM}(B^- \to D_s^- \phi) &\approx (4.2 \pm 0.2) \times 10^{-7}, \\ {\rm Br}^{\rm SM}(B^- \to D_s^- K^{*0}) &\approx (1.2 \pm 0.1) \times 10^{-8}, \end{aligned} \tag{18}$$

which are well below the present upper limits and are also consistent with the results of perturbative quantum chromodynamics calculation ${\rm Br}(B^+ \to D_s^+ \phi) = 3.0 \times 10^{-7}$ [11] and ${\rm Br}(B^+ \to D_s^+ K^{*0}) = (1.8 \pm 0.3) \times 10^{-7}$ [13].

Now we proceed to see the effect of unparticle stuff on the branching ratios and CP violation parameters. As seen from Eq. (9), the unparticle contribution contains three unknown parameters, namely, the dimension of the unparticle fields $d_{\mathcal{U}}$, the energy scale $\Lambda_{\mathcal{U}}$, and the coupling λ. Therefore, to see the effect of unparticles we fix the energy scale as $\Lambda_{\mathcal{U}} = 1$ TeV. Now using the CKM angle $\gamma = 70°$ we show in Figs. 1 and 2 the variations of the branching ratios and CP violation parameters with $d_{\mathcal{U}}$ for differ-

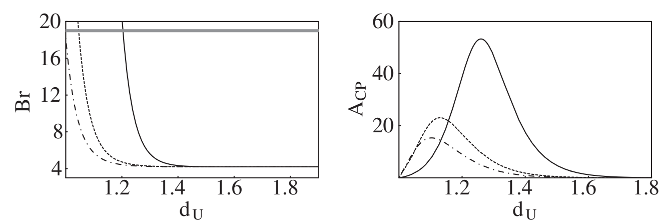

FIG. 1. CP averaged branching ratio $\langle {\rm Br}\rangle$ (in units of 10^{-7}) and CP violation parameter (in %) for the decay mode $B^- \to D_s^- \phi$, where the solid lines, dashed lines, and dot-dashed lines correspond to $\lambda = 1$, 0.1, and 0.05, respectively. The horizontal thick line in the branching ratio plot represents the experimental upper limit.

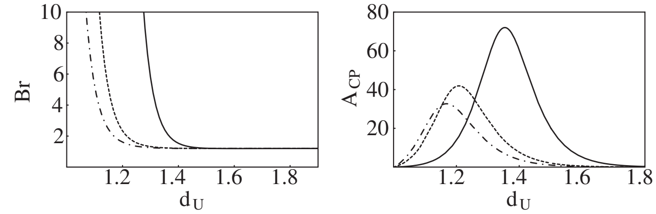

FIG. 2. CP averaged branching ratio $\langle {\rm Br}\rangle$ (in units of 10^{-8}) and CP violation parameter (in %) for the decay mode $B^- \to D_s^- K^{*0}$. The solid lines, dashed lines, and dot-dashed lines correspond to $\lambda = 1$, 0.1, and 0.05, respectively.

ent values of λ. From the figures we can see that when the scale dimension $d_{\mathcal{U}}$ is less than 1.4, the branching ratios are very sensitive to it and above $d_{\mathcal{U}} = 1.4$ the unparticle contributions are negligible and the branching ratio curves converge to the corresponding SM values. Furthermore, one can also obtain significant direct CP asymmetries due to the unparticle contributions. As seen from the figures, when the coupling $\lambda \approx \mathcal{O}(1)$, maximum CP violation, i.e., up to 50% (70%) is possible for the $B^- \to D_s^- \phi (B^- \to D_s^- K^{*0})$ channels. These CP violation parameters are also quite sensitive to the scale dimension $d_{\mathcal{U}}$, and above $d_{\mathcal{U}} \approx 1.6$ they approach to zero, which is the corresponding SM value.

Unparticle physics associated with a hidden scale invariant sector at a higher energy scale with a nontrivial fixed point has received significant attention in a short span of time. Many interesting unparticle specific signatures have been pointed out. In this work, we have explored another situation where we can expect clean unparticle signatures. We have studied the phenomenology of unparticle physics in the rare B decay channels $B^- \to D_s^- \phi (B^- \to D_s^- K^{*0})$. Since in the SM these decay modes have only annihilation contribution, the branching ratios are expected to be quite small. These values can be significantly enhanced from their SM values if unparticle effect is taken into account. The direct CP asymmetries for these modes are identically zero in the SM and therefore are very much suitable ones to look for new physics. Because of the presence of intrinsic CP conserving phase in the unparticle propagator nonzero and sizable direct CP violation can be observed in these modes. To conclude, enhancement in the branching ratios in the rare annihilation type B decays $B^- \to D_s^- \phi (B^- \to D_s^- K^{*0})$ and nonzero direct CP violation will be clean signals of new physics and unparticle physics will be a strong contender for the same.

The work of R. M. was partly supported by Department of Science and Technology, Government of India, through Grant No. SR/S2/HEP-04/2005. A. G. would like to thank Council of Scientific and Industrial Research, Government of India, for financial support.

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