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Radiative Decays: $B_C^{*\pm} \longrightarrow B_C^{\pm}\gamma$ in the Relativistic Independent Quark Model

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Abstract. We study the electromagnetic form factor of $B_c^{*\pm}$ meson decays via one photon radiative decays: $B_c^{*\pm} \to B_c^{*\pm}\gamma$ in the relativistic independent quark (RIQ) model based on a flavor independent average interaction potential in the scalar-vector harmonic form. The momentum dependent space like form factor is analytically continued from space like region $(q^2 \langle 0\,)$ to the physical time like region: $0 \leq q^2 \leq \left(M_{B_c^{*\pm}} - M_{B_c^{\pm}}\right)$ Our predictions of the coupling constant $g_{B_c^{*\pm} \to B_c^{*\pm}\gamma} = F_{B_c^* B_c}(q^2 = 0)$ and the decay width $\Gamma(B_c^{*\pm} \to B_c\gamma)$ are comparable to other model predictions. The decay width $\Gamma(B_C^{*\pm} \to B_C\gamma)$ which is proportional to $(\Delta m)^3 = (M_{B_c^{*\pm}} - M_{B_c^{\pm}})^3$, is found sensitive to $B_c^{*\pm}$ meson mass. This may help determine the unmeasured $B_c^{*\pm}$ meson mass expected at LHC in near future.

Keywords: Electromagnetic form factor, Coupling constant, Decay width

1. Introduction

The study of the B_c meson has been interesting due to its outstanding features. It is the lowest bound quarkonium state of two heavy (b, c) quarks with different flavors. Since it carries the flavor explicitly unlike the symmetric heavy quarkonium $(b\bar{b}, c\bar{c})$ states and its ground state lies below BD, BD*, B*D, B*D* thresholds, B_c meson decays weakly through $\bar{b} \to \bar{c}W^+$, $c \to sW^+$, $c\bar{b} \to W^+$ or decays radiatively through $b \to b\gamma, c \to c\gamma$ at the quark level. The pseudoscalar mesons $B_C^{\pm}$ decay weakly and have measurable lifetime, while the radiative decays: $B_c^{*\pm} \to B_c^{\pm}\gamma$ saturate the widths of vector mesons $B_c^{*\pm}$. The probe for the charm-beauty quarkonium (B_c) states has not been easier until recently as the energy scale involved is much higher for the available accelerators compared to that for $B_{u,d,s}$ states. By now the lifetime and mass of B_c meson have been experimentally measured [1-4] using semileptonic decays: $B_c^{\pm} \to J/\psi l^{\pm}\overline{\upsilon}_l, B_c^{+} \to J/\psi e^{+}\overline{\upsilon}_e$ and hadronic decays $B_c^{\pm} \to J/\psi\pi^{\pm}$, respectively. A more precise measurement of B_c- life time [5] has been possible recently by LHCb collaboration using decay mode: $B_c \to J/\psi\mu\nu_{\mu}X$, where X denotes any possible additional particle in the final states. However $B_c^{*\pm}$ mesons have not yet been observed experimentally, which is expected at large hadron collider (LHC) in near future through the radiative transitions. The radiative magnetic dipole decays: $B_c^{*\pm} \to B_c^{\pm}\gamma$ therefore bear significance both experimentally and theoretically.

Although one photo radiative decays of low lying heavy vector (V) to heavy pseudoscalar (P) meson have been investigated by several theoretical approaches: quark model [6-10], light cone QCD sum rules [11, 12] and heavy quark effective theory [13, 14], cloud bag model (CBM) [15], light front quark model (LFQM) [16,17], lattice QCD [18], three point QCD sum rules [19] and single quark transition (SQT) formalism [20] etc., only a few attempts have been made to study the momentum dependence of the relevant transition form factors. We have predicted the decay width of several M1 transitions ($V \to P\gamma$ and $P \to V\gamma$) in the relativistic independent quark (RIQ) model in static approximation [21] in reasonable agreement with available experimental data. A noticeable discrepancy in few such modes involving large momentum transfer obtained in our analysis based on static approximation was further improved in our subsequent analysis [2] by introducing recoil effect into the calculation, leading to better agreement of our results with the experimental data and other model predictions. In our recent analysis [22] we have studied the q^2-dependence of the relevant transition from factors $F_{VP\gamma}$ and predicted coupling constants $g_{VP\gamma}$ and decay widths for heavy flavored vector mesons: $D^*, D_s^*, J/\psi$ and B^*, B_s^*, Υ radiative decays in reasonable agreement with the available experimental data and other model predictions. However similar studies on $B_c^{*\pm} \to B_c^{\pm}\gamma$ decays have not been done in the (RIQ) model framework.

The purpose of this paper is to study the q^2- dependence of $F_{VP\gamma}$, and analytical continuation of the form factors from the space like region $(q^2 < 0)$ to the physical time like $(0 \le q^2 \le q^2_{\max})$ region and to evaluate of the relevant coupling constant and decay width of $B_c^{*\pm}$ radiative decays in the framework of our RIQ model. The model prediction in this sector would not only justify the applicability of RIQ model but offer robust signatures for the experiments to look for $B_c^{*\pm}$.

2. Radiative decay widths and Form Factors in the RIQ model

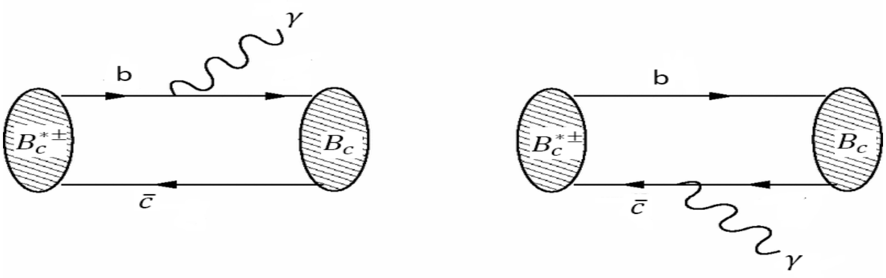

Fig. 1: Lowest-order graphs contributing to $B_c^{*\pm}$ radiative transitions

The radiative decay of $B_c^{*\pm} \to B_c^{\pm}\gamma$ depicted in Fig.1, is mainly single vertex process governed by the photon emission from independently confined quark or antiquark inside the $B_c^{*\pm}$ meson.The S-matrix element for the decay process in the configuration space can be written as

$$S_{B_C^* B_c} = \left\langle B_c\gamma \,|\, -ie\int d^4x T\left[\sum_q e_q \overline{\Psi}_q(x)\gamma^{\mu}\psi_q(x)A_{\mu}(x)\right] |\, B_c^* \right\rangle \tag{1}$$

Using usual quark field operator $\psi_q(x), \overline{\psi}_q(x)$ and the photon field $A_{\mu}(x)$ expansion, Eq. (1) can be expressed as

$$S_{B_C^* B_C} = i\sqrt{\alpha / k_0}\left\langle B_C \,|\, \sum_{q,\lambda,\lambda'} \frac{e_q}{e}\int \frac{dpdp'}{\sqrt{4E_p E_{p'}}}\delta^{(4)}(p'+k-p)\Lambda(p'\lambda'; p\lambda, k\delta) \,|\, B_C^* \right\rangle \tag{2}$$

where, $\Lambda(p'\lambda'; p\lambda; k\delta) = \bar{U}(p',\lambda')\gamma.\epsilon(k,\delta)U(p,\lambda)b_b^{+}(p',\lambda')b_b(p,\lambda)$

$$-\bar{V}(p,\lambda)\,\gamma.\epsilon V(p',\lambda')\,\tilde{b}_{\bar{c}}^{+}(p',\lambda')\tilde{b}_{\bar{c}}(p,\lambda)$$

In the RIQ model the meson state at definite momentum and spin is taken as an appropriate momentum wave packet [2, 23] in the form

$$|M(\vec{p},S_m)>=\frac{1}{\sqrt{N_M(\vec{p})}}\sum_{\lambda\lambda_{21}\in S_M}\xi^M_{q_1q_2}(\lambda_1,\lambda_2)\int d^3\vec{p}_{q2}d^3\vec{p}_{q\,2}\delta^{(3)}(\vec{p}_{q1}+\vec{p}_{q2}-\vec{p})$$

$$G_M(\vec{p}_{q1},\vec{p}_{q2})\hat{b}^+_{q1}(\vec{p}_{q1},\lambda_1)\hat{\tilde{b}}^+_{q2}(\vec{p}_{q2},\lambda_2)|0> \qquad (3)$$

where $\hat{b}^+_{q_1}(\vec{p}_{q_1},\lambda_1)$ and $\hat{\tilde{b}}^+_{q_2}(\vec{p}_{q_2},\lambda_2)$ are, respectively, the quark and antiquark creation operator, and $\xi^M_{q_1q_2}(\lambda_1,\lambda_2)$ is the SU(6)-spin flavor coefficients. $N_M(\vec{p})$ is the meson normalization factor of the wave packet. Incorporating the appropriate momentum wave packets for the initial and final meson states in Eq (2), the S-matrix element in the B_c^* meson rest frame can be obtained as

$$S_{VP}=i\sqrt{\alpha/k_0}\,\delta^{(4)}(p'+k-\hat{O}M_V)\left[Q(p',\vec{k})-\widetilde{Q}\,(p',\vec{k})\right] \qquad (4)$$

where $p'\equiv(E_p,p');\hat{O}\equiv(1,0,0,0),p'+\ \vec{k}=0$

$$Q(p',\vec{k})=\sum\frac{e_b}{e}\zeta^{B_c^*}_{b\bar{c}}(\lambda_1,\lambda_2)\,\zeta^{B_c}_{b\bar{c}}(\lambda_1',\lambda_2)\int dp_b\frac{G_{B_c^*}(\vec{p}_b,-\vec{p}_{\bar{c}})G_{B_c}(\vec{p}_b-\vec{k},-\vec{p}_{\bar{c}})}{\sqrt{4E_1E_{1k}\overline{N}_{B_c^*}(0)\overline{N}_{B_c}(p')}}$$

$$\times\,\overline{U}(-\vec{p}_b,\lambda_1')\gamma.\epsilon(k,\delta)U(\vec{p}_{b,}\lambda_1)$$

$$\tilde{Q}(p',\vec{k})=\sum\frac{e_{\bar{c}}}{e}\zeta^{B_c^*}_{b\bar{c}}(\lambda_1,\lambda_2)\zeta^{B_c}_{b\bar{c}}(\lambda_1,\lambda_2')\int dp_b\frac{G_{B_c^*}(\vec{p}_b,-\vec{p}_{\bar{c}})G_{B_c}(\vec{p}_{b-}\vec{k},-\vec{p}_{\bar{c}})}{\sqrt{4E_2E_{2k}\overline{N}_{B_c^*}\overline{N}_{B_c}(p')}}$$

$$\times\,\overline{V}(-\vec{p}_{\bar{c}},\lambda_2)\gamma.\epsilon(k,\delta)V(\vec{p}_b-\vec{k},\lambda_2') \qquad (5)$$

with $E_i=\sqrt{(p_{q_i}^2+m_{q_i}^2)}$and $E_{ik}=\sqrt{(\vec{p}_{q_i}-\vec{k})^2+m_{q_i}^2}$, i =1, 2. Here the energy conservation at the photon –hadron vertex is ensured by appropriate energy delta function using the usual approximation [2]: $E_1+E_2\cong M_V$ and$E_{1k}+E_2\cong E_{2k}+E_1=E_P$.Now making use of the explicit form of the Dirac spinors $U(\vec{p}_{b,}\lambda_1)$ and $V(\vec{p}_b,\lambda_2)$, the expressions for $Q(p',\vec{K})$ and $\tilde{Q}(p',K)$ are reduced to the form:

$$Q(\vec{k}) = \sum \frac{e_b}{e}\zeta_{bc}^{B^*}(\lambda_1,\lambda_2)\zeta_{bc}^{B}(\lambda_1',\lambda_2)\chi_{\lambda_1'}^{+}(\vec{\sigma}.\vec{K})\chi_{\lambda_1} I_b(\vec{k})$$

$$\tilde{Q}(\vec{k}) = \sum \frac{e_c}{e}\zeta_{bc}^{B^*}(\lambda_1,\lambda_2)\zeta_{bc}^{B}(\lambda_1,\lambda_2')\tilde{\chi}_{\lambda_2}^{+}(\vec{\sigma}.\vec{K})\tilde{\chi}'_{\lambda_2} I_c(\vec{k}) \qquad (6)$$

where $\overrightarrow{K} = \vec{k} \times \vec{\epsilon}(k,\delta)$

$$I_b = \int d\vec{p}_b \frac{G_{B_c^*}(\vec{p}_b, -\vec{p}_{\bar{c}})G_{B_c}(\vec{p}_b - \vec{k}, -\vec{p}_{\bar{c}})}{\sqrt{\bar{N}(0)\bar{N}(\vec{k})}} \sqrt{\frac{(E_1 + m_{q_1})(E_{1k} + E_2)}{4E_1E_{1k}(E_{1k} + m_{q_1})(E_1 + E_2)}}$$

(7)

$$I_{\bar{c}} = \int d\vec{p}_b \frac{G_{B_c^*}(\vec{p}_b, -\vec{p}_{\bar{c}})G_{B_c}(\vec{p}_b - \vec{k}, -\vec{p}_{\bar{c}})}{\sqrt{\bar{N}(0)\bar{N}(\vec{k})}} \sqrt{\frac{(E_2 + m_{q_2})(E_{2k} + E_1)}{4E_2E_{2k}(E_{2k} + m_{q_2})(E_1 + E_2)}}$$

Specifying the appropriate spin flavor coefficients $\zeta_{q_1q_2}^{M}(\lambda_1,\lambda_2)$ for B_c meson state and B_c^* meson state of different spin projections $S_V = (\pm 1,0)$, Eq. (4) can be further simplified to the form

$$S_{VP} = i\sqrt{\alpha/k_0}\,\delta^{(3)}(\vec{p} + \vec{k})\delta(E_P + k_0 + M_V)F_{VP}(q^2)K_{SV}$$

where

$$F_{B_c^*B_c}(q^2) = e_b I_b(m_b, m_{\bar{c}}, q^2) + e_{\bar{c}} I_{\bar{c}}(m_{\bar{c}}, m_b, q^2) \qquad (8)$$

$$K_{SV} = \left[\mp (K_1 \pm iK_2)/\sqrt{2}\,, K_3\right]$$

for $S_V = (\pm 1,0)$. A summation over photon polarization index δ and the vector meson spin S_V states yields a general relation

$$\sum_{\delta,S_V}|K_{SV}|^2 = 2k_\gamma^2 \qquad (9)$$

Finally summing over photon polarization and B_c meson spin appropriately and averaging over B_c^* meson spins, the partial decay widths for the $B_c^{*\pm} \to B_c^{\pm}\gamma$

radiative decays is realized in the standard form in terms of the outgoing photon energy $k_\gamma = \frac{M^2_{B^*_c} - M^2_{B_c}}{2M_{B^*_c}}$ and the coupling constant $g_{VP\gamma}$ as

$$\Gamma(B^*_c \to B_c\gamma) = \frac{\alpha}{3} g^2_{B^*_c B_c \gamma} k^3_\gamma \tag{10}$$

where the coupling constant $g_{VP\gamma}(k_\gamma)$ is obtained from $F_{B^*_c B_c}(q^2)$ in the limit $q^2 \to 0$.

3. Results and Discussion

For numerical analysis, we take the input parameters fixed from hadron spectroscopy and used in describing wide ranging hadronic phenomena [2, 23] as

$$(a, V_0) \equiv (0.017166\ GeV^3, -0.1375\ GeV)$$

$$(m_b, m_c, E_b, E_c) \equiv (4.77659, 1.49276, 4.76633, 1.57951) GeV \tag{11}$$

Although the masses of B_c and B_c^* mesons have been predicted in this model, we use the central value of the observed data $M^{\exp}_{B_C} = 6.275.1\ GeV$ [24] to reduce possible theoretical uncertainties. Since B_c^* meson mass is not yet experimentally measured, we consider our model mass $M_{B_C^{*\pm}} = 6.3078\ GeV$.

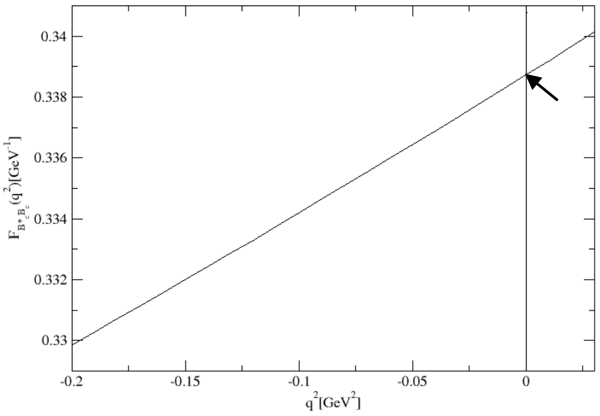

Fig. 2: The q^2 dependence of form factor $F_{B^*_c B_c}(q^2)$

Fig. 2 depicts the q^2- dependence of form factor $F_{B_c^* B_c}(q^2)$ where we have shown the analytical continuation of the form factor from space like $(q^2 < 0)$ region to the physical time like ($0 \le q^2 \le q^2_{\max}$) region using Eq. (7) and (8). Here $q^2_{\max} = (M_{B_C^*} - M_{B_C})^2$ corresponds the zero recoil point for the pseudoscalar B_c meson. The arrow in the figure represents the zero recoil point. The coupling constant $g_{B_c^* B_c}$ for real photon case is calculated from the expression of the form factor $F_{B_c^* B_c \gamma}$ in the limit $q^2 \to 0$ where the final state pseudoscalar meson (B_c) gets recoiled with maximum three momentum: $|\vec{k}| = \left({M^2}_{B_c^*} - M_{B_c}^2\right)/2M_{B_c^*}$ in the vector meson (B_c^*) rest frame. Our prediction of $g_{B_c^{*\pm} B_c^{\pm}\gamma} = 0.34\, GeV^{-1}$is comparable with the results of 0.273 [.257] $GeV^{-1}$for linear [HO] potential from LFQM [17] and 0.27 ± 0.095 GeV^{-1} from QCD sum rule approach [25].

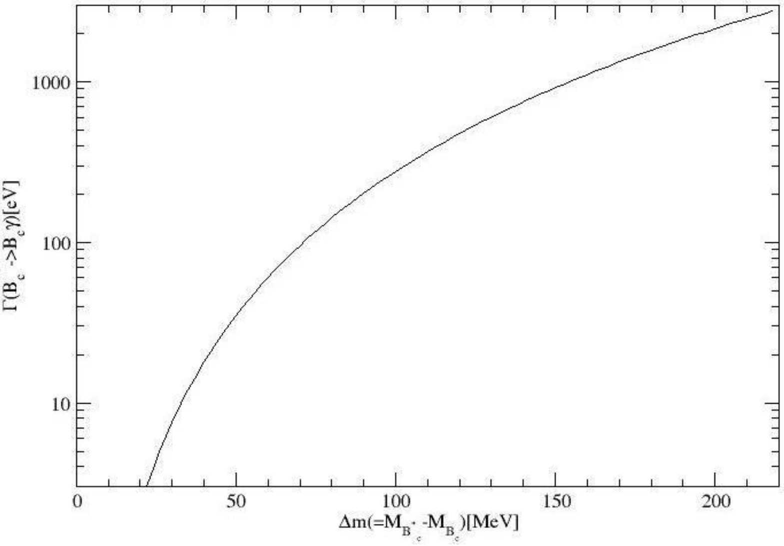

Fig. 3: Dependence of $\Gamma(B_c^{*\pm} \to B_c\gamma)$ on $\Delta m = M_{B_c^*} - M_{B_c}$

Finally for evaluation of decay width $\Gamma(B_c^{*\pm} \to B_c\gamma)$ from the predicted coupling constant using Eq. (10), the mass of B_c and B_c^* need to be specified. In the RIQ model we have predicted $M_{B_c^*} = 6.308\,GeV$ and accordingly our prediction of $\Gamma(B_c^* \to B_c\gamma) = 9.81\,eV$ is found in the same order of magnitude that of other theoretical predictions, i.e., 33 eV from the relativistic quark model [26], 59 eV from the Richardson's potential [27], 60 eV from the non-relativistic potential [28, 29], 80 eV from the relativized quark model [11] and 133.9 $\neq$ 79.7 eV from QCD sum rule approach [19].

For the unmeasured B_c^* meson mass, we also take some range of the B_c^* meson mass, i.e., $33\,MeV \leq \Delta m \left(= M_{B_c^*} - M_{B_c}\right) \leq 220\,MeV$.The lower value of Δm chosen here corresponds to our predicted B_c^* meson mass (i.e. $M_{B_c^*} = 6308\,MeV$). As one can see from Fig. 3., the dependence of $\Gamma(B_c^{*\pm} \to B_c\gamma)$ on Δm is quit sensitive to the B_c^* meson mass as is evident from our predicted decay width which is found to vary widely in the range $\Gamma(B_c^{*\pm} \to B_c\gamma) = 9.81 \sim 2824.28\,eV$ for $\Delta m = 33 \sim 220\,MeV$. This sensitivity for the B_c^* radiative decay may help in determining B_c^* meson mass experimentally which is expected at LHC in near future and pin down RIQ model as one of the suitable models of hadrons.

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