Charmed quark fragmentation in $B$-mesons decays

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It is well known that large nonfragmentational contributions to inclusive production of charmed particles appear at low energies. In the case of charm production in $B$-meson decays these contributions arise from the participation of the light valent quark from the $B$-meson and can be easily described phenomenologically. These contributions affect $D$-meson spectra and essentially change ratios between yields of different $D$-meson states.

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Recent study of $D^{(*)}$-mesons and $\Lambda_C$-baryons production in the $e^+e^-$-annihilation have shown that differential production cross-sections of these particles in 10-90 GeV energy range can be obtained using the framework of fragmentation functions [1]. One and the same nonperturbative fragmentation function was used in the whole energy range while the energy dependence was incorporated in the perturbative fragmentation function. Thus the nonperturbative fragmentation function depended only on the type of final particle.

The usage of the fragmentational approach for $D^{(*)}$-mesons and $\Lambda_C$-baryons production in the $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B} \rightarrow D^{*} + X, \Lambda_C + X$ process is arguable due to the low mass of the $B$-meson. Nonetheless good agreement with the experimental data has been attained for the $\Lambda_C$ momentum distribution in this process. This is not the case for the $D^{(*)}$-mesons, whose spectrum has an additional contribution with the momentum higher than predicted.

One of the possible explanations is that the light valent quark in the $B$-meson can take part in the charmed meson formation and lead to the higher momentum of the latter than the fragmentational mechanism. This valent quark can not affect the baryon production as an $(ud)$-diquark-spectator is needed for the $\Lambda_C$ formation. This mechanism must lead to the correlation between quark compositions of the decaying and forming mesons.

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The BABAR collaboration have measured inclusive $B^{-}$ and $B^{0}$ decays to flavor-tagged $D$-mesons. Momentum distributions for $D^{+}$, $D^{-}$, $D^{0}$ and $D^{0}$ in the $B$ rest frame are presented. These data allow to check the aforesaid conjecture. Though experimental data concern scalar mesons which appear in the decays of vector $D^{*}$-mesons more often than by themselves. That is why it is important to account for the $D^{*}$-mesons decays.

Let us first consider the $D^{*}$ production. The same will refer to the scalar $D$-mesons born directly, not in the $D^{*}$ decay. To fix the idea we will talk about the $B^{-}$-meson decays. $B^{0}$ decays through weak channel and we are interested in the $c$ and $\bar{c}$ momentum spectra in $b \rightarrow c(p_c)f_1f_2$ and $b \rightarrow c\bar{c}(p_{\bar{c}})s$ processes. Differential widths of this processes are equal $\Gamma(p_c,m_1,m_2)$ and $\Gamma(p_{\bar{c}},m_c,m_s)$ while

$$\frac{d\Gamma}{dp}(p,m_1,m_2) = \frac{G_F^2p^2}{12\pi^3E(m_b^2 + m_c^2 - 2mbE)^3} \theta \left( m_b^2 - 2mbE + m_c^2 - (m_1 + m_2)^2 \right) \sqrt{m_b^2 + m_c^2 - 2mbE - (m_1 - m_2)^2} \sqrt{m_b^2 + m_c^2 - 2mbE - (m_1 + m_2)^2} [3m_b^2E - 2m_b^5(9m_c^2 + 8p^2) + m_b^4E \left( 45m_c^2 + 28p^2 \right) + m_b^2E \left( -4p^2(-7m_c^2 + m_1^2 + m_2^2) + 45m_1^4 + 3\left( m_1^2 - m_2^2 \right)^2 \right) + 2m_b^3 \left( -36p^2m_c^2 - 30m_1^4 + p^2\left( m_1^2 + m_2^2 - 8p^2 \right) \right) + 3m_c^2E \left( m_c^4 - \left( m_1^2 - m_2^2 \right)^2 \right) + 2m_b \left( p^2(-8m_1^2 + (m_1^2 + m_2^2)m_2^2 + (m_1^2 - m_2^2)^2) - 9m_1^6 + 3\left( m_1^2 - m_2^2 \right)^2m_2^2 \right)]$$

where $E = \sqrt{(p^2 + m_c^2)}$, and $m_1$ and $m_2$ denote masses of particles $f_1$ and $f_2$. These particles may be pair of light quarks $\bar{u}$ and $d$, $\bar{c}s$-pair or leptonic pairs $e\bar{\nu}_e$, $\mu\bar{\nu}_\mu$ and $\tau\bar{\nu}_\tau$. Masses of these particles are assumed to be $m_b = 5.0$ GeV, $m = 1.7$ GeV, $m_s = m_c = m_\mu = 0$, $m_\tau = 1.8$ GeV. For the quark sector the corresponding widths are enhanced by the color factor of 3. Momentum distribution of the $\bar{c}$-quark obviously coincide with those of the $c$-quark accompanied by the $\bar{c}s$ pair production. Momentum of the $b$-quark within $B$-meson is supposed to be Gaussian with the width of 400 MeV. Resulting spectra of the $c$ and $\bar{c}$-quarks are presented in Fig. II.

For the momenta distribution of charmed mesons the factorizational relation is used:

$$\frac{d\sigma_D}{dx} = \frac{d\sigma_{c\bar{c}}}{dx} \otimes D(z),$$

where $x = p_D/p_c^{\text{max}}$ is the reduced momentum of the meson and $D(z)$ is the fragmentational function. For both $D$ and $D^{*}$-mesons the KLP fragmentation function is used to
describe the fragmentational contribution. The only parameter of this function $\alpha = 3.6$ was determined by fitting the high energy data on $D^{(*)}$-meson production in $e^+e^-$-annihilation. While it is important to account for perturbative part of fragmentational function at high energies, it can be neglected in our case as it does not appreciably differ from the $\delta$-function at the $m_B$-scale.

For the $D^{(*)0}$ production we modify the fragmentation function in the following way:

$$D_{D^0}^{np}(z) = \frac{1}{2}(1 - A)\frac{\Gamma(\alpha + 3)}{\Gamma(\alpha + 1)} z^\alpha (1 - z) + A \delta(1 - z),$$

where first term is traditional KLP function and the second corresponds to the recombination with the spectator. For the $D^{(*)+}$-mesons recombination is not possible as there is no $\bar{d}$-quark in the $B^-$. Thus the KLP term is the only term in the $D^{(*)+}$ fragmentation function:

$$D_{D^+}^{np}(z) = \frac{1}{2}(1 - A)\frac{\Gamma(\alpha + 3)}{\Gamma(\alpha + 1)} z^\alpha (1 - z).$$

One can see that such modification changes not only the shape but also the normalization of the fragmentational function. Nevertheless the sum of the fragmentation functions of $D^{(*)+}$ and $D^{(*)0}$ does not change as we still have one $c$-quark to hadronize. The $D^{(*)-}$ and $\bar{D}^{(*)0}$ formation is possible through the $\bar{c}$-quark fragmentation. The recombination is not possible for them and the same functions with $A = 0$ are used.

Charmed quark hadronizes to $D^*$ with larger probability than to $D$. The ratio of these probabilities is denoted by $C$ and was varied to describe the experimental data most accurately. $D^* \rightarrow D + \pi$ and $D^* \rightarrow D + \gamma$ decays occur with well known branching fractions and are elaborated in [6].

Regarding the aforementioned points partial widths of the decays considered are written
where $\Gamma_{\text{tot}}$ is the total width of the $B$ to all $D$-states decay.

Best agreement with the experimental distributions is found with the values $A = 0.6$ and $C = 2$. This value of $C$ is in between the naive spin counting estimation ($C = 3$) and the value $C = 1.4$, measured in the $Z$-boson decays [4]. The comparison of the partial widths with the experimental results is presented in Tab. I. All the values are within the error ranges. Many experimental uncertainties cancel when considering ratios of yields of charm-correlated and anticorrelated particles of every type. This ratios are shown in Tab. II and also do not contradict the experimental values.

Apart from the partial widths momentum distributions of the $D$-mesons in the $B$ rest frame can be obtained. They are presented in Fig. 2 and 3.
TABLE II: The fraction of anti-correlated $B$-meson decays compared to the BABAR collaboration data [2].

| Fraction                              | BABAR Data     |
|---------------------------------------|----------------|
| $Br_{B^-\rightarrow D^0+X}/Br_{B^-\rightarrow D^+X}$ | 0.092, 0.098 ± 0.007 ± 0.001 |
| $Br_{B^-\rightarrow D^-+X}/Br_{B^-\rightarrow D^+X}$ | 0.237, 0.204 ± 0.035 ± 0.001 |
| $Br_{B^0\rightarrow D^0+X}/Br_{B^0\rightarrow D^0+X}$ | 0.138, 0.146 ± 0.022 ± 0.006 |
| $Br_{B^0\rightarrow D^-+X}/Br_{B^0\rightarrow D^+X}$ | 0.072, 0.058 ± 0.028 ± 0.006 |

To sum it up, it was shown that the fragmentational approach has to be supplemented with the recombination terms in $B$-meson decays. The part of recombination is significant and is up to 75% in the $D^{*0}$ formation. Simple phenomenological treatment of this process consists in supplementing the fragmentation function with a $\delta$-term.

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FIG. 2: Momentum distributions of the $B^{-} \rightarrow D^{0}$, $B^{-} \rightarrow D^{+}$, $B^{-} \rightarrow \bar{D}^{0}$ and $B^{-} \rightarrow D^{-}$ decays (from top to bottom).
FIG. 3: Momentum distributions of the $\bar{B}^0 \to D^0$, $\bar{B}^0 \to D^+$, $\bar{B}^0 \to \bar{D}^0$, $\bar{B}^0 \to D^-$ decays (from top to bottom).