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The observation possibility of B_c excitations at LHC

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It is shown that in the decays $B_c(2P) \to B_c^* \gamma^{\rm hard}$, $B_c(3P) \to B_c^* \gamma^{\rm hard}$ and $B_c(2S) \to B_c^* + \pi^+\pi^-$ followed by the decay $B_c^* \to B_c + \gamma^{\rm soft}$ the loss of the soft photon $\gamma^{\rm soft}$ do not wash out peaks from the initial excitations. The relative yields of B_c^*, $2P$-wave, and $3P$-wave states of B_c meson at LHC are estimated as function of transverse energy of emitted photon $\gamma^{\rm hard}$. It is pointed out, that the decays $B_c(2S) \to B_c(B_c^*) + \pi^+\pi^-$ could provide a new information about a σ resonance nature.

The XXI International Workshop High Energy Physics and Quantum Field Theory
June 23 – June 30, 2013
Saint Petersburg Area, Russia

*Speaker.

PoS(QFTHEP 2013)051

1. Introduction

The first observation of B_c-meson ground state was performed by CDF and D0 experiments (Tevatron) in two decay modes: $B_c \to J\psi l\nu$ $(l = e, \mu)$ and $B_c \to J\psi\pi$ [1–4]. For now, the B_c meson is observed also by LHC experiments in the following decay modes: $B_c \to J\psi\pi$ (LHCb, CMS, ATLAS [5–7]), $B_c \to J\psi\pi\pi\pi$ (LHCb and CMS [6, 8]), $B_c^+ \to \psi(2S)\pi^+$, $B_c^+ \to J/\psi D_s^+$ and $B_c^+ \to J/\psi D_s^{*+}$, $B_c^+ \to J/\psi K^+$ (LHCb [9–11]).

B_c-meson is a nonrelativistic doubly heavy system, and like $b\bar{b}$- and $c\bar{c}$-states, can be considered within the potential model, which predicts 19 bounded $b\bar{c}$-states below the decay threshold to $B\bar{D}$ (see [12–15]). Contrary to $b\bar{b}$- or $c\bar{c}$-quarkoniums, there are no strong annihilation decay modes for $b\bar{c}$-states, and this makes the $b\bar{c}$ system similar to usual $b\bar{q}$ or $c\bar{q}$-meson. All excited B_c-mesons decay via cascade electromagnetic or hadronic transitions to the ground state.

There are some differences in the production of ordinary quarkonium with hidden flavor and the production of B_c-meson. The necessity to produce two heavy quark pairs, $b\bar{b}$ and $c\bar{c}$, leads to the strong suppression of B_c production cross section:

$$\sigma_{B_c} \sim 10^{-3}\sigma_B. \tag{1.1}$$

It is natural, that the difference in production mechanisms leads to the difference in the relative yield of excited states. Contrary to the production of quakonia with hidden flavor, the production of P-wave B_c states is suppressed comparing to S-wave states. The mechanism of B_c states production was studied theoretically in [16–29]. According to these investigations the B_c-meson production can be interpreted as a b-quark fragmentation (like fragmentation $b \to B$) only at high transverse momenta ($p_T > 35$ GeV). The ratio $R_{B_c} = \sigma(B_c^*)/\sigma(B_c)$ between production cross sections of vector and pseudoscalar ground states predicted within the fragmentation approach is about 1.4. At low and middle p_T the recombination mechanism dominates and gives $R_{B_c} \sim 2.6$. Thus, the value R_{B_c} could provide the essential information about the production mechanism. Unfortunately, as it shown in this paper, the experimental measurement of R_{B_c} is currently impossible due to the low energy release in $B_c^* \to B_c\gamma$ decay, which leads to the essential difficulties in the B_c^* identification.

The analysis below shows, that electromagnetic transitions $B_c(2P) \to B_c(1S)\gamma$ and hadronic transitions $B_c(2S) \to B_c(1S)\pi\pi$ are the more perspective for the experimental observation, than the process $B_c^* \to B_c\gamma$, in spite of that the total yield of B_c^* is several times lager.

2. Electromagnetic decays of B_c^* and P-wave B_c states

The mass difference between the lowest vector and pseudoscalar states of $\bar{b}c$-quarkonium (B_c^* and B_c) predicted within potential models is fairly small:

$$M(B_c^*) - M(B_c) \approx 65 \text{ MeV}. \tag{2.1}$$

It is practically impossible to detect the photon with the transverse energy about 65 MeV at LHC experiments. Even the LHCb experiment, which is designed for low p_T physics, can not detect a photon with the transverse energy smaller, than 300 MeV approximately. Therefore the decaying B_c^* must have a quite large transverse momentum to be observed. The production cross section rapidly decreases with increasing of the transverse momentum, and this leads to significant decreasing of event number, where such a photon could be detected.

According to the expression for the maximum transverse energy of photon

$$\omega_T^{max} = \left(1 + \frac{\Delta M}{2M_{B_c^*}}\right)\left(\sqrt{M_{B_c^*}^2 + p_T^2} + p_T\right)\frac{\Delta M}{M_{B_c^*}} \approx 0.01\left(\sqrt{M_{B_c^*}^2 + p_T^2} + p_T\right) \tag{2.2}$$

the photons with transverse energy $\omega_T > 0.5$ GeV can be produced by B_c^*-mesons with $p_T(B_c^*) >$ 24 GeV. Such a cut on transverse momentum reduces the yield of B_c^*-mesons approximately by two orders of magnitude. It should be noted that there is no such a problem for $2P$-wave B_c states, at least for LHCb experiment. Even $B_c(2P)$-mesons with low transverse momentum are able to produce the fairly hard photon (see tab. 1). Therefore, despite the low relative yield of $2P$-wave excitations (about 10-20% v.s. $\sim$60% for B_c^*), the $2P$-wave excitations need smaller efforts to be detected. Rough estimations show, that a number of photons with $\omega_T > 0.5$ GeV from P-wave states is $25 \div 50$ times larger, than from B_c^* mesons:

$$\frac{\sigma_{2P}(\omega_T^\gamma > 0.5 \text{ GeV})}{\sigma_{1S}(\omega_T^\gamma > 0.5 \text{ GeV} \Longleftrightarrow p_T(B_c) > 24 \text{ GeV})} \sim 25 \div 50. \tag{2.3}$$

It should be stressed that only about 20% of all $2P$-wave states emit only one photon, immediately transforming to the lowest pseudoscalar state:

$$B_c(2P1^+) \xrightarrow[\sim 13\%]{\gamma} B_c(1^1S_0),$$

$$B_c(2P1^{'+}) \xrightarrow[\sim 94\%]{\gamma} B_c(1^1S_0).$$

In all other cases $2P$-wave excitations decay through intermediate B_c^* state, consequentially emitting a “hard” photon and a “soft” one:

$$B_c(2P) \xrightarrow{\gamma^{\text{hard}}} B_c(1^3S_1) \xrightarrow{\gamma^{\text{soft}}} B_c(1^1S_0).$$

The second (“soft”) photon will be lost almost always. However, this doesn’t prevent the experimental observation of $2P$-wave states of B_c-meson. Indeed, it can be easily shown, that the loss of “soft” photon in the cascade decay of $2P$-wave states broadens the peak by the value

$$\Delta\tilde{M} \approx 2\frac{\Delta M \Delta M'}{M} \tag{2.4}$$

and shifts it to the left by ΔM, where $\Delta M = M(B_c^*) - M(B_c)$ and $\Delta M' = M(B_c^P) - M(B_c^*)$.

The numerical value of broadening for $2P$-wave states can be obtained from (2.4) by putting $\Delta M \approx 65$ MeV and $\Delta M' \approx 400$ MeV:

$$\Delta\tilde{M}_{2P} \approx 10 \text{ MeV}.$$

It is clear, that this width is smaller than the apparatus width of resonance and doesn’t affect the observation possibility at all. The broadening value for $3P$-wave states is also small:

$$\Delta\tilde{M}_{3P} \approx 20 \text{ MeV}.$$

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Table 1: Radiative decays of B_c meson P-wave excitations (see [15, 30, 31]).

initial state	final state	Br, %	ΔM, MeV
2^3P_0	$1^3S_1+\gamma$	100	363-366
$2P1^+$	$1^3S_1+\gamma$	87	393-400
	$1^1S_0+\gamma$	13	393-400
$2P1'^+$	$1^1S_0+\gamma$	94	472-476
	$1^3S_1+\gamma$	6	472-476
2^3P_2	$1^3S_1+\gamma$	100	410-426
3^3P_0	$1^3S_1+\gamma$	2	741
$3P1^+$	$1^3S_1+\gamma$	8.5	761
	$1^1S_0+\gamma$	3.3	820
$3P1'^+$	$1^1S_0+\gamma$	22.6	825
	$1^3S_1+\gamma$	0.7	769
3^3P_2	$1^3S_1+\gamma$	18	778

Table 2: The relative yield of excited B_c states in the decay mode $B_c+\gamma$ as function of a minimal transverse energy of photon $\omega_T^{\min}$.

$\omega_T^{\min}$, GeV	B_c state	relative yield %
0.3	$B_c(2P)$	~ 5.0
	$B_c(3P)$	~ 1.0
	B_c^*	~ 0.8
0.5	$B_c(2P)$	~ 3.5
	$B_c(3P)$	~ 0.7
	B_c^*	~ 0.06
1.0	$B_c(2P)$	~ 0.9
	$B_c(3P)$	~ 0.4
	B_c^*	~ 0.005

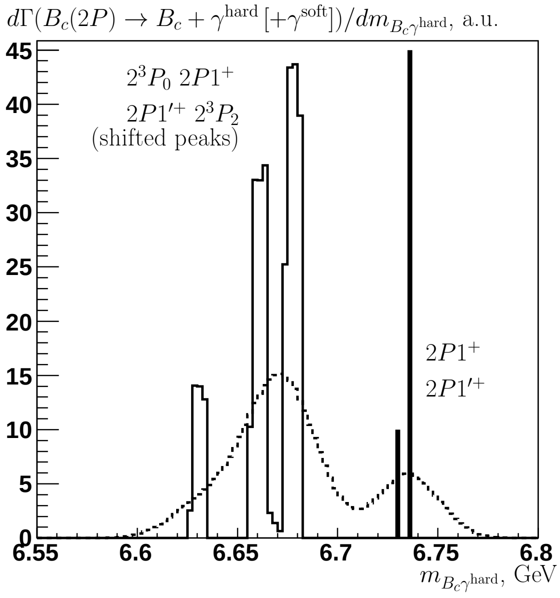

Figure 1: The mass spectrum of $B_c+\gamma^{\rm hard}$ system for the process $B_c(2P)\to B_c+\gamma^{\rm hard}[+\gamma^{\rm soft}]$.

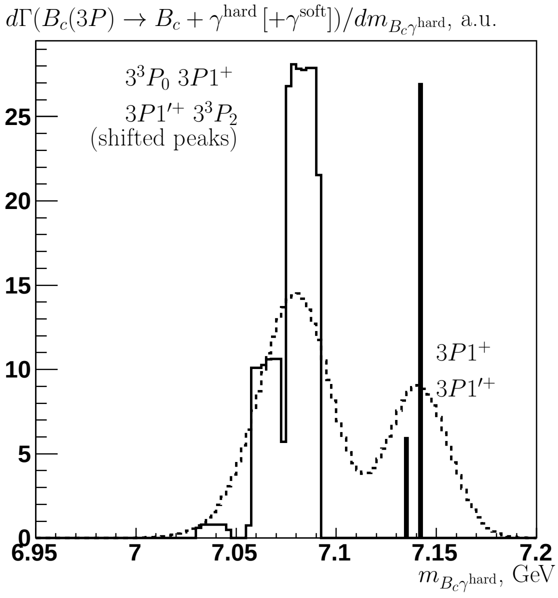

Figure 2: The mass spectrum of $B_c+\gamma^{\rm hard}$ system for the process $B_c(3P)\to B_c+\gamma^{\rm hard}[+\gamma^{\rm soft}]$.

The predicted distribution over $B_c+\gamma^{\rm hard}$ invariant mass for the cascade decays of $2P$-wave states is shown in fig. 1. Solid histograms correspond to the shifted and broadened peaks from 2^3P_0, $2P\ 1^+$, $2P\ 1'^+$ and 2^3P_2. Unshifted peaks from $2P\ 1^+$ and $2P\ 1'^+$ states are conventionally marked by bold vertical lines. To take into account the apparatus resolution, this distribution is convoluted with a Gaussian function with a dispersion 15 GeV (see the dashed histogram). Of cause, such a simulation doesn't reflect real properties of detector. Nevertheless, it gives a rough idea about shapes of peaks, which could be observed at LHC experiments.

Similar distributions for $3P$-wave states are shown in fig. 2.

It is important to note that in spite of practically the same yield of $2P$-wave and $3P$-wave states in the proton-proton interactions, the observation of $3P$-wave excitations in $B_c + \gamma$ spectrum is more difficult. The thing is that $2P$-excitations always decays via electromagnetic transitions, while only 20% of $3P$-wave states decay electromagnetically.

The relative yields of $2P$-wave and $3P$-wave states in $B_c + \gamma$ decay mode for various minimal transverse energies of photon are given in tab. 2. It is seen from this table, that the larger transverse energy of a photon, the smaller probability, that it comes from B_c^*-meson.

3. $B_c(2S) \to B_c(1S) + \pi\pi$ decays

There is every reason to expect, that in the long term the LHC experiments will allow us to observe not only P-wave states, but also $2S$-wave excitations of B_c-meson. Indeed, the yield of $2S$ is about 25% of total B_c-meson yield and approximately a half of them decay to B_c (B_c^*) and $\pi^+\pi^-$ pair:

$$B_c(2^1S_0) \xrightarrow[\sim 50\%]{\pi^+\pi^-} B_c(1^1S_0),$$

$$B_c(2^3S_1) \xrightarrow[\sim 40\%]{\pi^+\pi^-} B_c(1^3S_1),$$

$$\sigma(B_c(2S))/\sigma^{\text{total}}(B_c) \sim 25\ \%,$$

$$\sigma(2^3S_1)/\sigma(2^1S_0) \sim 2.6.$$

Therefore about 10% of observed B_c-mesons originate from the decay $B_c(2S) \to B_c(B_c^*) + \pi^+\pi^-$. However, the separation of the signal from the background for such processes is a very complicated experimental task. In this paper we restrict ourselves to discussion about the signal shape, which could be observed after the cut-off of background. The only thing that we want to mention here, that the background conditions strongly depend on B_c transverse momentum. Therefore it could be supposed, that the higher momentum will have a $B_c(2S)$-meson, the more favorable background conditions will be for that event. If it is so, the high p_T experiments like CMS and ATLAS will be more suitable for the research of $B_c(2S)$, than LHCb. Of course the detailed estimations are needed to prove or disprove this hypothesis.

It would be very interesting to compare the experimentally measured spectra of the $\pi\pi$-pair invariant mass for decays $B_c(2S) \to B_c + \pi^+\pi^-$ and $\psi' \to \psi + \pi^+\pi^-$. The last one is investigated theoretically since 1970s. In [32 – 35] it was concluded within the chiral theory, that at small $\pi\pi$ masses the process amplitude is approximately proportional to $m^2_{\pi\pi} - 4m^2_\pi$. This approximation was extended to the total phase space of decay. Currently this simplest approach is used in LHCb for simulation of the discussed events. However, the data of BESII experiment [36] shows, that the contribution of σ-resonance [1] to this process should also be considered. It is likely, that $B_c(2S)$-mesons emit the $\pi\pi$-pair via the same or similar mechanisms, as ψ', therefore the role of σ-meson could be also essential in the decays $B_c(2^3S_1) \to B_c^* + \pi^+\pi^-$ and $B_c(2^1S_0) \to B_c + \pi^+\pi^-$.

It should be noted that there is no consensus about the nature of σ-meson. The authors of [37] consider the σ-meson as a dynamically generated resonance in $\pi\pi$ interactions. Within the approach developed in [38, 39] it is a mixed state of two-quark and four-quark states.

The role of σ-meson in $D_1(2430) \to D\pi\pi$ decay was studied in [39].

As for the electromagnetic decays of P-wave excitations, the loss of "soft" photon in B_c^* decay shifts the vector $2S$-wave state approximately by 65 MeV and insignificantly broadens the peak:

$$\Delta\tilde{M}_{2S} \approx 2\frac{\Delta M\sqrt{\Delta M''^2 - M_{2\pi}^2}}{M} \approx 10\ \text{MeV}, \tag{3.1}$$

where $\Delta M = M(B_c^*) - M(B_c)$ and $\Delta M'' = M(B_c(2^3S_1)) - M(B_c^*)$. As a result, the visible peak from the vector 2^3S_1 state in $B_c + \pi\pi$ spectrum will appear 30 MeV to the left from the pseudoscalar 2^1S_0 state, in spite of that 2^3S_1 excitation is about 40 MeV heavier, than 2^1S_0 one (see the solid histogram in fig. 3).

The apparatus resolution is taken into account by convolution of this distribution with a Gaussian function with a dispersion 15 GeV. It could be concluded, that if two these peaks will be resolved in the experiment due to small distance, a single asymmetric peak will be seen (the dashed histogram in fig. 3).

4. Conclusion

It is shown in this work that the loss of "soft" photon from the decay $B_c^* \to B_c + \gamma$ shifts the peaks of $2S$-, $2P$- and $3P$-excitations by 65 MeV and broadens them by $10-20$ MeV. This doesn't preclude the study of B_c excitations.

In early theoretical works on the hadronic B_c-meson production it was shown that the ratio $R_{B_c} = \sigma(B_c^*)/\sigma(B_c)$ could provide an essential information about the B_c production mechanism. Unfortunately, is it extremely difficult to measure this ratio due to a small energy release in the $B_c^* \to B_c\gamma$ decay. Most likely, $2P$-wave excitations will be found first in the $M_{B_c} + \gamma$ spectrum.

It is also shown, that decays $B_c(2S) \to B_c(B_c^*) + \pi^+\pi^-$ decays may appear to be a

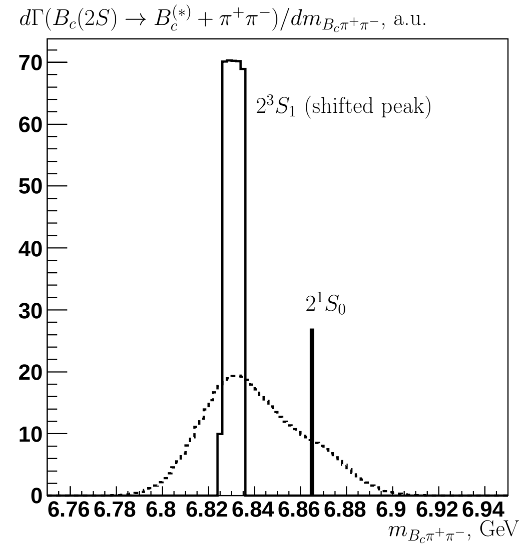

Figure 3: Mass spectrum of $B_c + \gamma^{\text{hard}}$ system for the process $B_c(2S) \to B_c + \pi\pi[+\gamma_{\text{lost}}]$.

[1] σ or $f_0(500)$: $J^{PC} = 0^{++}$, $m = (400-550) - i(200-350)$ MeV.

source of new information about the nature
of σ-meson.

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