PRODUCTION OF THE DOUBLY HEAVY BARYONS, B_c MESON AND THE ALL-CHARM TETRAQUARK AT AFTER@LHC WITH DOUBLE INTRINSIC HEAVY MECHANISM*

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(Received November 28, 2016; accepted March 6, 2017)

In the paper, we discuss contribution of the doubly intrinsic heavy mechanism into the production of B_c meson, the doubly heavy baryons and the all-charm tetraquark at a future fixed-target experiment at the LHC (AFTER@LHC). The production cross sections and the mean values of Feynman-x for the final states are presented.

DOI:10.5506/APhysPolB.48.163

1. Introduction

The low statistics NA3 experiment measurements of the double J/ψ production [1, 2] and the observation of the doubly charmed baryons by the SELEX Collaboration [3–5] cannot be described with the perturbative QCD. In Refs. [6, 7], the importance of the double intrinsic charm as the leading production mechanism is shown. However, this kind of physics is very limitedly accessible at the current collider experiments. The future high luminosity fixed-target experiment utilizing the 7 TeV LHC beam (AFTER@LHC) can provide wide opportunity for getting a new data at the high Feynman-x at a center-of-mass energy $\sqrt{s} = 115$ GeV [8–12].

The existence of a non-perturbative intrinsic heavy quark component in the nucleon is a rigorous prediction of QCD. Intrinsic charm and bottom quarks are in the wave function of a light hadron — from diagrams where the heavy quarks are multiply attached by gluons to the valence quarks [13, 14]. In this case, the frame-independent light-front wave function of the light hadron has maximum probability when the Fock state is minimally off-shell. This occurs when all of the constituents are at rest in the hadron rest frame and thus have the same rapidity y when the hadron is boosted. Equal rapidity occurs when the light-front momentum fractions $x = \frac{k^+}{P^+}$ of the Fock state constituents are proportional to their transverse mass: $x_i \propto m_{\mathrm{T},i} = \sqrt{m_i^2 + k_{\mathrm{T},i}^2}$; *i.e.* when the heavy constituents have the largest momentum fractions. This feature underlies the Brodsky, Hoyer, Peterson, and Sakai (BHPS) model for the distribution of intrinsic heavy quarks [15, 16].

In the BHPS model, the wave function of a hadron in QCD can be represented as a superposition of Fock state fluctuations, *e.g.* $|h\rangle \sim |h_l\rangle + |h_l g\rangle + |h_l Q\bar{Q}\rangle \ldots$, where $Q = c, b$ and h_l, as above, is light quark content. When the projectile interacts with the target, the coherence of the Fock components is broken and the fluctuation can hadronize. The intrinsic heavy flavor Fock components are generated by virtual interactions such as $gg \to Q\bar{Q}$ where gluon couple to two or more projectile valence quarks. The probability to produce such $Q\bar{Q}$ fluctuations scales as $\alpha_{\mathrm{s}}^2(m_Q^2)/m_Q^2$, relative to leading-twist production.

Following [6, 15, 16], the general formula for the probability distribution of an n-particle intrinsic heavy flavor Fock state as a function of x_i and transverse momentum $\vec{k}_{\mathrm{T},i}$ can be written as

$$\frac{\mathrm{d}P_{iQ}}{\prod_{i=1}^n \mathrm{d}x_i \mathrm{d}^2 k_{\mathrm{T},i}} \propto \alpha_{\mathrm{s}}^4 \left(M_{Q\bar{Q}}\right) \frac{\delta\left(\sum_{i=1}^n \vec{k}_{\mathrm{T},i}\right) \delta\left(1 - \sum_{i=1}^n x_i\right)}{\left(m_h^2 - \sum_{i=1}^n m_{\mathrm{T},i}^2/x_i\right)^2}\,, \tag{1}$$

where m_h is mass of the initial hadron. The probability distribution for the production of two heavy quark pairs is

$$\frac{\mathrm{d}P_{iQ_1Q_2}}{\prod_{i=1}^n \mathrm{d}x_i \mathrm{d}^2 k_{\mathrm{T},i}} \propto \alpha_{\mathrm{s}}^4 \left(M_{Q_1\bar{Q}_1}\right) \alpha_{\mathrm{s}}^4 \left(M_{Q_2\bar{Q}_2}\right) \frac{\delta\left(\sum_{i=1}^n \vec{k}_{\mathrm{T},i}\right) \delta\left(1 - \sum_{i=1}^n x_i\right)}{\left(m_h^2 - \sum_{i=1}^n m_{\mathrm{T},i}^2/x_i\right)^2}\,. \tag{2}$$

If we are interested in calculation of the x distribution, then we can simplify the formula with replacement of $m_{\mathrm{T},i}$ with the effective mass $\hat{m}_i = \sqrt{m_i^2 + \langle k_{\mathrm{T},i}^2 \rangle}$ and neglect the mass of the light quarks

$$\frac{\mathrm{d}P_{iQ_1Q_2}}{\prod_{i=1}^n \mathrm{d}x_i} \propto \alpha_{\mathrm{s}}^4 \left(M_{Q_1\bar{Q}_1}\right) \alpha_{\mathrm{s}}^4 \left(M_{Q_2\bar{Q}_2}\right) \frac{\delta\left(1 - \sum_{i=1}^n x_i\right)}{\left(\sum_{i=1}^n \hat{m}_{\mathrm{T},i}^2/x_i\right)^2}\,. \tag{3}$$

This model assumes that the vertex function in the intrinsic charm wave function is relatively slowly varying; the particle distributions are then controlled by the light-cone energy denominator and phase space. The Fock states can be materialized by a soft collision in the target which brings the state on shell. The distribution of produced open and hidden charm states will reflect the underlying shape of the Fock state wave function.

In this paper, we shall investigate the doubly intrinsic heavy approach for the production of the doubly heavy states in the Feynman-x region at a fixed-target experiment at the LHC at $\sqrt{s} = 115$ GeV.

2. The double heavy states production cross section under the quark–hadron duality

2.1. Production from $|uudc\bar{c}c\bar{c}\rangle$ Fock states

In the frame of the quark–hadron duality, the production cross section of the doubly heavy state can be estimated as the production of a heavy quark pair with small invariant mass between the heavy quark production threshold and the threshold of production open heavy flavor hadrons. In the case of the doubly charmed baryons

$$m_c + m_c < M_{cc} < m_{\mathrm{th}} = m_D + m_D \,, \tag{4}$$

where m_c is c-quark mass, m_D is D-meson mass. The production cross section of the doubly charmed baryons can be written as

$$\sigma(\Xi_{cc}) \approx \tfrac{2}{3}\, f_{cc/p}\, \sigma_{icc} \,, \tag{5}$$

where the factor $2/3$ comes from requirement of isolating color-antitriplet. The cc pair has $3 \times 3 = 9$ color components, 3 color-antitriplets, and 6 color-sixtets. There is $1/3$ probability for the color-antitriplet possibility. The $f_{cc/p}$ is the fraction of the cc pairs in the duality interval produced by a proton beam

$$f_{cc/p} \simeq \int\limits_{4m_c^2}^{m_{\mathrm{th}}^2} \mathrm{d}M_{cc}^2 \frac{\mathrm{d}P_{icc}}{\mathrm{d}M_{cc}^2} \Bigg/ \int\limits_{4m_c^2}^{s} \mathrm{d}M_{cc}^2 \frac{\mathrm{d}P_{icc}}{\mathrm{d}M_{cc}^2} \,, \tag{6}$$

and σ_{icc} is the double intrinsic charm cross section

$$\begin{aligned} \sigma_{icc} &= \frac{P_{icc}}{P_{ic}}\, \sigma_{ic} \,, \\ \sigma_{ic} &= P_{ic}\, \sigma_{pp}^{\mathrm{in}} \frac{\mu^2}{4\hat{m}_c^2} \,, \end{aligned} \tag{7}$$

$\mu^2 \approx 0.2$ GeV^2 denotes the soft interaction scale parameter; following the BHPS model, we will assume $P_{ic} = 0.01$. In Ref. [6], it is found that for proton, $P_{icc} \approx 20\%\, P_{ic}$. The proton–proton inelastic scattering cross section $\sigma_{pp}^{\rm in}$ is (for $\sqrt{s} \geq 100$ GeV) [17]

$$\sigma_{pp}^{\rm in} = 62.59\, \hat{s}^{-0.5} + 24.09 + 0.1604\, \ln(\hat{s}) + 0.1433\, \ln^2(\hat{s})\ {\rm mb}\,, \tag{8}$$

where $\hat{s} = s/2m_p^2$. At the AFTER@LHC energies, $\sqrt{s} = 115$ GeV, $\sigma_{pp}^{\rm in}$ equals to 28.4 mb. The numerical value of the production cross section of the doubly charmed baryons will be

$$\sigma(\Xi_{cc}) \approx 9.4 \times 10^4\ {\rm pb}\,.$$

The $x_{\rm F}$-distribution of Ξ_{cc} baryons can be written as

$$\frac{{\rm d}P_{icc}(\Xi_{cc})}{{\rm d}x} = \int \prod_{i=1}^{n} {\rm d}x_i \frac{{\rm d}P_{icc}}{{\rm d}x_1 \ldots {\rm d}x_n} \times \delta(x_\Xi - x_c - x_c)\,. \tag{9}$$

Figure 1 shows the normalized $x_{\rm F}$-distribution. The mean $x_{\rm F}$ value is 0.33.

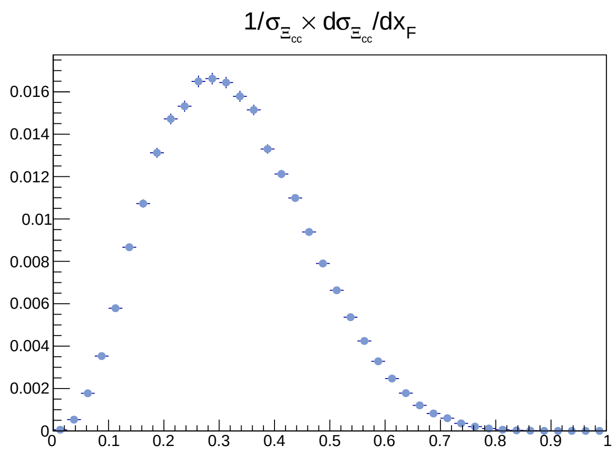

Fig. 1. The histogram represents calculation of the $x_{\rm F}$-distribution of the doubly charmed baryons in the double intrinsic charm model.

It is interesting to estimate the production of the all-charm tetraquark T_{4c} which can be naturally produced from the $|uudc\bar{c}c\bar{c}\rangle$ Fock state. The most recent prediction of the all-charm tetraquark scalar state mass is $m(T_{4c}) = 5.3 \pm (0.5)$ GeV [18]. Then the duality interval will be

$$m_{J/\psi} + m_{J/\psi} < M_{c\bar{c}c\bar{c}} < m_{\Xi_{cc}^+} + m_{\Xi_{cc}^+}\,, \tag{10}$$

where $m_{J/\psi}$ and $m_{\Xi_{cc}^+} = 5.32$ GeV [3] are masses of the J/ψ meson and the lightest doubly charmed baryons respectively. The production cross section will be

$$\sigma(T_c) \approx R\, f_{c\bar{c}c\bar{c}}\, \sigma_{icc} = R \times 10^4\ {\rm pb}\,,$$

where the positive number $R < 1$. It used to be assumed 0.1. Figure 2 shows the normalized $x_{\rm F}$-distribution. The mean $x_{\rm F}$ value is 0.67.

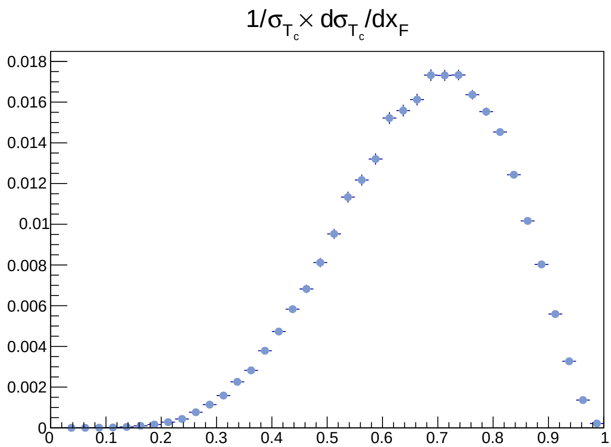

Fig. 2. The histogram represents calculation of the $x_{\rm F}$-distribution of the all-charmed tetraquark (T_{4c}) in the double intrinsic charm model.

2.2. Production from $\left|uudc\bar{c}b\bar{b}\right\rangle$ Fock states

Following the above method, we can calculate production of the B_c meson and the beauty-charmed baryons. The duality interval for both states is

$$m_c + m_b < M < m_{\rm th} = m_D + m_B \,, \tag{11}$$

where m_b is b-quark mass and m_B is B-meson mass. Then we obtain

$$\sigma(B_c) \approx f_{bc/p}\, \sigma_{icb} \,, \tag{12}$$

$$\sigma(\Xi_{bc}) \approx \tfrac{2}{3}\, f_{\bar{b}c/p}\, \sigma_{icb} \,, \tag{13}$$

where $f_{bc/p}$ and $f_{\bar{b}c/p}$ are, respectively, the fraction of the bc and $\bar{b}c$ pairs in the duality interval. Following [19, 20], the cross section for $|uudc\bar{c}b\bar{b}\rangle$ configuration in a proton is

$$\begin{aligned} \sigma_{icb} &= \frac{P_{icb}}{P_{ib}}\, \sigma_{ib} \,, \\ \sigma_{ib} &= P_{ic}\, \sigma_{pp}^{\rm in} \frac{\mu^2}{4\hat{m}_b^2} \left(\frac{\hat{m}_c}{\hat{m}_b}\right)^4 \left(\frac{\alpha_{\rm s}(\hat{m}_{b\bar{b}})}{\alpha_{\rm s}(\hat{m}_{c\bar{c}})}\right)^4 . \end{aligned} \tag{14}$$

Assuming that $P_{icb}/P_{ib} \approx P_{icc}/P_{ic}$, we obtain the numerical value of the production cross section

$$\sigma(B_c) \approx 3.9 \times 10^2 \text{ pb}\,, \tag{15}$$
$$\sigma(\Xi_{bc}) \approx 2.6 \times 10^2 \text{ pb}\,. \tag{16}$$

The $x_{\rm F}$-distribution is similar to the distribution of the doubly charmed baryons (see Fig. 1) but the mean value is 0.37.

2.3. Production from $\left|uud b\bar{b} b\bar{b}\right\rangle$ *Fock states*

It is easy to estimate the production of the doubly beauty baryons from the $|uud b\bar{b} b\bar{b}\rangle$ Fock states. The duality interval will be $m_b + m_b < M < m_{\rm th} = m_\Upsilon + m_\Upsilon$. The production cross section of the doubly beauty baryons, as above, is

$$\sigma(\Xi_{bb}) \approx \tfrac{2}{3}\, f_{\bar{b}b/p}\, \sigma_{ibb}\,, \tag{17}$$

where, following the BHPS model, $\sigma_{ibb} = (\hat{m}_c/\hat{m}_b)^2\, \sigma_{icb}$. The numerical value of the production cross section of the doubly beauty baryon is 50 pb.

3. Summary

We present the production properties of B_c meson, the doubly heavy baryons and the all-charm tetraquark T_{4c} at a future fixed-target experiment AFTER@LHC. It is clear that not all heavy diquarks hadronize into proposed finale states, therefore, we need to interpret the presented cross sections as the upper limit. Also it is interesting to compare our predictions with the single intrinsic charm mechanism predictions given in Ref. [21] (see Table I).

TABLE I

Production cross section of the doubly heavy baryons at the AFTER@LHC. The second column shows predictions in the double heavy intrinsic model and the third presents predictions in the single intrinsic charm model.

Particle type	This work	Ref. [21]
Ξ_{cc}	9.4×10^4 pb	4×10^3 pb
Ξ_{bc}	2.6×10^2 pb	8.95 pb
Ξ_{bb}	50 pb	3.1×10^{-2} pb

It is easy to see that the doubly intrinsic heavy mechanism becomes the leading production mechanism at high Feynman-x (see also discussion in Ref. [22]).

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