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Doubly heavy baryon production at $\gamma\gamma$ collider

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Abstract

The inclusive production of doubly heavy baryons Ξ_{cc} and Ξ_{bb} at $\gamma\gamma$ collider is investigated. It is found that the contribution from the heavy quark pair QQ in color triplet and color sextet are important.

Keywords: Doubly heavy baryon; NRQCD; Linear collider

1. Introduction

$\gamma\gamma$ collider is one option of the International Linear Collider (ILC) in the future, where many interesting issues can be employed [1]. The doubly heavy baryon production is a potential one. It can be factorized into two stages, i.e., the production of two heavy quarks and their transformation into the baryon. The heavy quark mass sets the large scale, which enables us to calculate their creation within perturbative QCD framework. The transformation is nonperturbative, and may be dealt with non-relativistic QCD (NRQCD) because of the small velocity of the heavy quark in the rest frame of the baryon [2]. This provides us a good opportunity to study QCD, both in the perturbative and nonperturbative aspects. For this aim, a fully inter-course between phenomenological and experimental investigations in various processes is required.

The doubly heavy baryon Ξ_{cc} has been observed by SELEX Collaboration [3–5], and many theoretical studies have been done, e.g., in Refs. [6–10]. However, up to now, we cannot understand its production mechanism sufficiently yet. As pointed out in Ref. [11], the observed production rate is much larger than most of the theoretical predictions, which means that further investigation on the production mechanism as well as exploration for more experimental opportunities are still necessary.

For two identical heavy quark system, if one neglects the relative orbital angular momentum, there are only two states due to the anti-symmetry of the total wave function. One is in angular momentum ${}^3S_1$ and color triplet, and the other is ${}^1S_0$ and color sextet. In general, both of these two states can contribute to the doubly heavy baryon production, which can be described by introducing two hadronic matrix elements [8,12]. In Refs. [6,7] the inclusive production of doubly heavy baryons at various colliders is studied, where only the contribution from quark pair in ${}^3S_1$ and color triplet is included. While in Refs. [8–10], the contribution from both color triplet and color sextet is taken into account for e^+e^- and hadron–hadron colliders. In this Letter, our aim is to investigate the inclusive production of doubly heavy baryons at the future $\gamma\gamma$ collider.

This Letter is organized as follows: In Section 2, we list the basic formula for $\gamma\gamma \to H_{QQ} + X$ and give some related numerical results. The effective cross sections for Ξ_{cc} and Ξ_{bb} production at ILC are presented in Section 3. Finally a short summary is given.

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2. Doubly heavy baryon production in $\gamma\gamma$ collisions

The doubly heavy baryon H_{QQ} can be produced via the following process

$$\gamma(p_1) + \gamma(p_2) \to H_{QQ}(k) + X, \tag{1}$$

where p_1, p_2 and k respectively denote the four-momentum of the corresponding particles. The unobserved state X can be divided into a nonperturbative part X_N and a perturbative part X_P. At tree level, X_P consists of two heavy anti-quarks $\bar{Q}\bar{Q}$. Adopting the notation in Ref. [8], one can obtain the scattering amplitude for $\gamma(p_1) + \gamma(p_2) \to H_{QQ}(k) + \bar{Q}(p_3) + \bar{Q}(p_4) + X_N$ process

$$\mathcal{T} = \frac{1}{2}\int \frac{d^4k_1}{(2\pi)^4} A_{ij}(k_1, k_2, p_3, p_4) \int d^4x_1\, e^{-ik_1\cdot x_1} \langle H_{QQ}(k) + X_N|\bar{Q}_i(x_1)\bar{Q}_j(0)|0\rangle, \tag{2}$$

where k_1, k_2 denote the four-momentum of the internal heavy quarks, and p_3, p_4 the momentum of the anti-quarks. i, j represent Dirac and color indices, $Q(x)$ is the Dirac field for the heavy quark.

The differential cross section for $\gamma(p_1) + \gamma(p_2) \to H_{QQ}(k) + \bar{Q}(p_3) + \bar{Q}(p_4) + X_N$ is

$$\begin{aligned} d\hat{\sigma}(\hat{s}) = {} & \left(\frac{1}{4}\right)\frac{1}{2\hat{s}} \sum_{X_N} \frac{d^3\mathbf{k}}{(2\pi)^3} \int \frac{d^3p_3}{(2\pi)^3 2E_3} \frac{d^3p_4}{(2\pi)^3 2E_4} (2\pi)^4\delta^4(p_1 + p_2 - k - p_3 - p_4 - P_{X_N}) \\ & \times \frac{1}{4}\int \frac{d^4k_1}{(2\pi)^4}\frac{d^4k_3}{(2\pi)^4} A_{ij}(k_1, k_2, p_3, p_4)\big(\gamma^0 A^\dagger(k_3, k_4, p_3, p_4)\gamma^0\big)_{kl} \\ & \times \int d^4x_1\, d^4x_3\, e^{-ik_1\cdot x_1 + ik_3\cdot x_3} \langle 0|Q_k(0)Q_l(x_3)|H_{QQ} + X_N\rangle\langle H_{QQ} + X_N|\bar{Q}_i(x_1)\bar{Q}_j(0)|0\rangle, \end{aligned} \tag{3}$$

where the average over polarization of the photons and the summation over the spin of the baryon H_{QQ} and over color, spin state of two $\bar{Q}$ quarks is implied, and $\hat{s} = (p_1 + p_2)^2$. The factor 1/4 in the bracket is induced by the identical photons and anti-quarks. The non-relativistic normalization for the heavy baryon is used here. Employing the translation invariance to eliminate the sum over X_N, one can obtain

$$\begin{aligned} d\hat{\sigma}(\hat{s}) = {} & \frac{1}{2\hat{s}}\frac{d^3\mathbf{k}}{(2\pi)^3} \int \frac{d^3p_3}{(2\pi)^3 2E_3}\frac{d^3p_4}{(2\pi)^3 2E_4} \int \frac{d^4k_1}{(2\pi)^4}\frac{d^4k_3}{(2\pi)^4} A_{ij}(k_1, k_2, p_3, p_4) \\ & \times \big(\gamma^0 A^\dagger(k_3, k_4, p_3, p_4)\gamma^0\big)_{kl} \int d^4x_1\, d^4x_2\, d^4x_3\, e^{-ik_1\cdot x_1 - ik_2\cdot x_2 + ik_3\cdot x_3} \\ & \times \frac{1}{16}\langle 0|Q_k(0)Q_l(x_3)a^\dagger(\mathbf{k})a(\mathbf{k})\bar{Q}_i(x_1)\bar{Q}_j(x_2)|0\rangle, \end{aligned} \tag{4}$$

where $a^\dagger(\mathbf{k})$ is the creation operator for H_{QQ} with three momentum $\mathbf{k}$. This contribution can be represented by Fig. 1, where the black box represents the Fourier transformed matrix element. In the framework of NRQCD, at the zeroth order of the relative velocity between heavy quarks in the rest frame of H_{QQ}, the hadronic matrix element is [8]

$$\begin{aligned} & v^0 \int d^4x_1\, d^4x_2\, d^4x_3\, e^{-ik_1\cdot x_1 - ik_2\cdot x_2 + ik_3\cdot x_3} \langle 0|Q_k^{a_3}(0)Q_l^{a_4}(x_3)a^\dagger(\mathbf{k})a(\mathbf{k})\bar{Q}_i^{a_1}(x_1)\bar{Q}_j^{a_2}(x_2)|0\rangle \\ & \quad = (2\pi)^4\delta^4(k_1 - m_Q v)(2\pi)^4\delta^4(k_2 - m_Q v)(2\pi)^4\delta^4(k_3 - m_Q v)\big[-(\delta_{a_1a_4}\delta_{a_2a_3} + \delta_{a_1a_3}\delta_{a_2a_4})(\tilde{P}_v C\gamma_5 P_v)_{ji}(P_v\gamma_5 C\tilde{P}_v)_{lk}\cdot h_1 \\ & \qquad + (\delta_{a_1a_4}\delta_{a_2a_3} - \delta_{a_1a_3}\delta_{a_2a_4})\big(\tilde{P}_v C\gamma^\mu P_v\big)_{ji}\big(P_v\gamma^\nu C\tilde{P}_v\big)_{lk}(v_\mu v_\nu - g_{\mu\nu})\cdot h_3\big], \end{aligned} \tag{5}$$

where m_Q is the mass of the heavy quark, a_i ($i = 1, 2, 3, 4$) and i, j, k, l respectively denote the color and Dirac indices, and

$$P_v = \frac{1 + \gamma\cdot v}{2}, \qquad C = i\gamma^2\gamma^0, \qquad v^\mu = k^\mu/M_{H_{QQ}}. \tag{6}$$

$\tilde{P}_v$ is the transpose of the matrix P_v. h_1 (h_3) represents the probability for a QQ pair in ${}^1S_0$ (${}^3S_1$) state and in the color state of 6 ($\bar{3}$) to transform into the baryon,

$$\begin{aligned} h_1 &= \frac{1}{48}\langle 0|\big[\psi^{a_1}\varepsilon\psi^{a_2} + \psi^{a_2}\varepsilon\psi^{a_1}\big]a^\dagger a\psi^{a_2\dagger}\varepsilon\psi^{a_1\dagger}|0\rangle, \\ h_3 &= \frac{1}{72}\langle 0|\big[\psi^{a_1}\varepsilon\sigma^n\psi^{a_2} - \psi^{a_2}\varepsilon\sigma^n\psi^{a_1}\big]a^\dagger a\psi^{a_2\dagger}\sigma^n\varepsilon\psi^{a_1\dagger}|0\rangle, \end{aligned} \tag{7}$$

where σ^j ($j = 1, 2, 3$) are Pauli matrices, $\varepsilon = i\sigma^2$ is totally anti-symmetric, ψ is the NRQCD field for the heavy quark. Generally, h_1 and h_3 should be determined by nonperturbative QCD. Under NRQCD, h_1 and h_3 are at the same order. h_3 can be related to the