THE BOTTOM BARYON PAIR PRODUCTION IN
THE $e^+e^-$-ANNIHILATION

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Abstract

In the framework of the nonrelativistic diquark model of the heavy baryons and the perturbative approach of QCD we predict the value and energy dependence for the total cross section of the $\Lambda_b$- and $\Sigma_b^*$-baryons pair production at the energy range of the KEKB and PEP-II $e^+e^-$-colliders.

1 Introduction

At the present time the existence of the heavy baryons containing $b$-quark is confirmed experimentally with the high order of accuracy. The mass, the lifetime and the main partial widths of the decays are measured for the lightest of the bottom baryon $\Lambda_b \ (I(J^{P}) = 0(1^{+}))$ in the experiments at $p\bar{p}$–colliders CERN [1] and FNAL [2] as well as at $e^+e^-$–collider LEP [3] in the $Z$-boson pole. Recently the first evidence of the $\Sigma_b, \Sigma_b^*$ [4] and $\Xi_b$ [5] baryons was obtained at LEP too. The great surprise is to be a large depolarization of the $\Lambda_b$ baryons produced in the $Z$ boson decays $\mathcal{P}_{\Lambda_b} = -0.23^{+0.24}_{-0.20}$ [3], which contradict the naive predictions [6] that the main part of the initial polarization of the bottom quark to transfer to the $\Lambda_b$ baryon $\mathcal{P}_{\Lambda_b} \approx \mathcal{P}_b = -0.94$. Howere, the accuracy of the obtained results on the bottom baryon production at the high energy $p\bar{p}$ and $e^+e^-$ colliders isn’t enough for the precise testing the theoretical predictions.

The main reasons of it are the small luminosity of the high energy colliders $\mathcal{L} \sim 10^{30}$ sm$^{-2}$s$^{-1}$ and the nonresonant nature of the heavy quark production processes. By means of this point, the more careful conditions for the study of the $b$-quark baryons are waiting at the future $B$-factories KEKB and PEP-II at the energy range of $e^+e^-$–collisions is about of 11-14 GeV and the high luminosities $\mathcal{L} \sim 10^{34}$sm$^{-2}$s$^{-1}$. The exclusive bottom baryon-antibaryon pair production is a very interesting subject for the study of the heavy baryon physics at the $B$-factories. The cross sections, as a function of the total $e^+e^-$ beam energy $\sqrt{s}$, of these processes have a resonance like

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nature and clean experimental signatures. With the theoretical point of view the processes of the exclusive baryon pair creation near the threshold of the bottom quarks production are more calculable in the framework of QCD and the quark-diquark model of the baryons.

Here we study the processes of the bottom baryon-antibaryon spin-3/2 and spin-1/2 pair production in the $e^+e^-\text{annihilation}$ at the energies of KEKB and PEP-II $e^+e^-\text{colliders}$: $e^+e^-\to \Lambda_b\bar{\Lambda}_b$ and $e^+e^-\to \Sigma^*_b\bar{\Sigma}^*_b$.

### 2 The model

Recently [8, 9] we have suggested the approach based on the perturbative QCD and the nonrelativistic diquark model of the baryons, which let us to calculate the cross sections and spin asymmetries for the heavy and doubly heavy baryon production. In the framework of the diquark model of the baryons [10] the heavy baryon may be presented as a system of the heavy quark Q and the diquark D. In the case of the bottom baryon it has $m_Q, m_D >> \Lambda_{QCD}$ ($m_Q \sim 5 \text{ GeV}, m_D \sim 1 \text{ GeV}$) and we can use the perturbative expansion in $\alpha_s$, taking into account the nonperturbative effects by diquark form factors. Because of the reduced mass of the heavy quark - diquark system is large in compare with the binding energy (it is the same order as for charmonium), we shall use the nonrelativistic approximation for the description of the quark-diquark transition into the baryon. In the approximation of the zero binding energy and small relative velocity of the constituents, the probability of the quark-diquark transition into the baryon is determined by the baryon wave function in the origin $\Psi(0)$ [11]. This parameter may be calculated using the potential approach with the quark-diquark potential which have been fixed in the calculating of the heavy baryon masses [12].

The amplitudes of the processes $e^+e^-\to \Lambda_b\bar{\Lambda}_b, \Sigma^*_b\bar{\Sigma}^*_b$ are described by Feynman diagrams which are shown in Fig.1. The contribution of the diagrams 3 and 4 may be omitted because of the strong suppressions due to the diquark form factor in the photon-diquark vertexes [13].

In such a way, the virtual photon create the bottom quark-antiquark pair (diagrams 1 and 2 in Fig.1), which catch the scalar or the vector diquark, correspondingly. The gluon couplings to scalar and vector diquarks are presented by the following expressions [10]:

$$S^a_{\mu} = -ig_sT^a(p_D' - p_D)_{\mu}F_s(k^2)$$  \hspace{1cm} (1)

2
\( V_\mu = i g_s T^a [\epsilon^*_D \epsilon'_D (p'_D - p_D)_\mu F_1(k^2) + [(p_D \epsilon'_D) \epsilon^*_D (p'_D) \epsilon'_D (p'_D - p_D)_\mu F_2(k^2) + (\epsilon'_D p_D)(\epsilon^*_D p'_D)(p_D - p'_D)_\mu F_3(k^2)], \) (2)

where \( T^a \) are Gell-Mann matrices, \( \epsilon^*_D \) and \( \epsilon'_D \) are the diquark polarization vectors, \( p_D = r p \) and \( p'_D = r p' \) are diquark four-momenta, \( F_s, F_1, F_2 \) and \( F_3 \) are form factors depending on the momentum transfer squared \( k^2 = (p_D + p'_D)^2 = r^2 s \). At first approximation the form factors don’t depend on the baryon type and may be parameterized as the same \([13]\), where the authors fit successfully the angular distributions of the baryons in the processes \( \gamma \gamma \rightarrow p \bar{p}, \Lambda \bar{\Lambda} \) and \( J/\Psi \rightarrow p \bar{p}, \Lambda \bar{\Lambda} \). We shall use the following set of form factors:

\[
F_s(k^2) = \frac{Q_s^2}{Q_s^2 - k^2},
\]

(3)

\[
F_1(k^2) = \left( \frac{Q_v^2}{Q_v^2 - k^2} \right)^2,
\]

(4)

\[
F_2(k^2) = (1 + \kappa) F_1(k^2),
\]

(5)

\[
F_3(k^2) \approx 0,
\]

(6)

where \( Q_s^2 = 3.22 \text{ GeV}^2 \), \( Q_v^2 = 1.50 \text{ GeV}^2 \) and \( \kappa = 1.39 \) being the anomalous chromomagnetic moment of the vector diquark, and all form factors are restricted to value smaller than 1.3.

In the case of the \( \Lambda_b \)-baryon production it has fusion of the heavy quark and scalar diquark. After some simplifications we have obtained:

\[
\mathcal{M}(e^+ e^- \rightarrow \Lambda_b \bar{\Lambda}_b) = \frac{4}{9} \left[ \frac{\Psi(0)}{2 m_D} \right]^2 \frac{(e e_b)^2 g_s^2}{r^2 s^3} L_\alpha H_{1/2}^\alpha,
\]

(7)

where

\[
L_\alpha = \bar{V}(p^+) \gamma_\alpha U(p^-),
\]

\[
H_{1/2}^\alpha = \bar{U}(p) \left[ (\hat{p} - \hat{p}') (\hat{p} + \hat{p}_D + m_Q) \gamma^\alpha + \gamma^\alpha (m_Q - \hat{p}' - \hat{p}_D) \right] V(p'),
\]

\( e_b = 1/3, \ e^2 = 4 \pi \alpha, \ g_s^2 = 4 \pi \alpha_s(m_D), \ 4/9 \) is the colour factor of the amplitude. The spinors \( \bar{U}(p) \) and \( V(p') \) describe \( \Lambda_b \)-baryons in the final state.
The amplitude for the $e^+e^-\text{-annihilation into spin-3/2 } \Sigma_b^*\text{-baryons, corresponding to fusion of the heavy quark and the vector diquark, can be written as follows:}

$$\mathcal{M}(e^+e^- \rightarrow \Sigma_b^*\Sigma_b^*) = \frac{4}{9} \left[ \frac{\Psi(0)}{2m_D} \right]^2 \frac{(ee_b)^2 g_s^2}{r^2 s^3} L_\alpha H^\alpha_{3/2};$$  \hfill (8)

where

$$H^\alpha_{3/2} = \bar{\Psi}_\sigma(p) \left[ \gamma^\mu(p + \hat{p}_D + m_Q)\gamma^\alpha + \gamma^\alpha(m_Q - \hat{p}' - \hat{p}_D)\gamma^\mu \right] \Psi_\lambda(p'),$$

$$\left\{ F_1(k^2)(p' - p)_\mu g_{\sigma\lambda} + F_2(k^2)[p_\lambda g_{\mu\sigma} - p_\sigma g_{\mu\lambda}] \right\},$$

$\bar{\Psi}_\sigma(p)$ and $\Psi_\lambda(p')$ are the Rarita-Schwinger spinors for the spin-3/2 baryons.

### 3 The results

The differential cross section for the processes $e^+e^- \rightarrow \Lambda_b\bar{\Lambda}_b, \Sigma_b^*\bar{\Sigma}_b$ can be written as follows:

$$\frac{d\sigma}{dt} = \frac{|\mathcal{M}|^2}{16\pi s^2}.\hfill (9)$$

The total cross section $\sigma(s)$ will be obtained after integration over $t$ in limits:

$$t_{\text{min}} = M^2 - \frac{s}{2}(1 - v), \quad t_{\text{max}} = M^2 - \frac{s}{2}(1 + v).$$

where $v = \sqrt{1 - 4M^2/s}$. The integrating can be made analytically, we have found that

$$\sigma(e^+e^- \rightarrow \Lambda_b\bar{\Lambda}_b) = \frac{4\pi e^2_b\alpha_s^2 |R(0)|^4 v}{2187 \frac{m_D^6}{s}} \Phi_1(r, v) F_1^2(k^2),$$  \hfill (10)

$$\sigma(e^+e^- \rightarrow \Sigma_b^*\bar{\Sigma}_b) = \frac{4\pi e^2_b\alpha_s^2 |R(0)|^4 v}{2187 \frac{m_D^6}{s}} \left[ \Phi_{11}(r, v) F_1^2(k^2) + \Phi_{22}(r, v) F_2^2(k^2) + \Phi_{12}(r, v) F_1(k^2) F_2(k^2) \right],$$  \hfill (11)
where $R(0) = \frac{\Psi(0)}{\sqrt{4\pi}}$ is the radial part of the baryon wave function in the origin,

$$\Phi_s(r, v) = \frac{9}{16} \left[ v^8 r(r - 2) + 2 v^6 (-3 r^2 + 6 r - 4) + 4 v^4 (3 r^2 - 6 r + 7) + 2 v^2 (-5 r^2 + 10 r - 16) + 3 (r^2 - 2 r + 4) \right]$$

$$\Phi_{11}(r, v) = \frac{1}{4} \left[ 3 v^8 r(r - 2) + 2 v^6 (-11 r^2 + 22 r - 12) + 4 v^4 (15 r^2 - 30 r + 29) + 2 v^2 (-37 r^2 + 74 r - 104) + 33 (r^2 - 2 r + 4) \right]$$

$$\Phi_{22}(r, v) = 2 \left[ v^8 r(r - 1) + 4 v^6 (-2 r^2 + 2 r - 1) + v^4 (23 r^2 - 23 r + 22) + 4 v^2 (-7 r^2 + 7 r - 10) + 12 (r^2 - r + 2) \right]$$

$$\Phi_{12}(r, v) = v^8 r(r - 2) + v^6 (9 r^2 + 18 r - 8) + v^4 (29 r^2 - 58 r + 52) + 3 v^2 (-13 r^2 + 26 r - 36) + 18 (r^2 - 2 r + 4).$$

The results of our calculations are presented in the Table 1 for the maximum values of the total cross sections and ratios:

$$R_{\Lambda, \Sigma} = \frac{\sigma(e^+ e^- \rightarrow \Lambda_b \bar{\Lambda}_b, \Sigma^*_b \bar{\Sigma}^*_b)}{\sigma(e^+ e^- \rightarrow bb)},$$

where

$$\sigma(e^+ e^- \rightarrow bb) = 3 e^2_b \alpha_s^2 \frac{4 \pi \alpha_s^2}{3 s} \left( 1 + \frac{2 m_Q^2}{s} \right) \sqrt{1 - \frac{4 m_Q^2}{s}}.$$
GeV. The curve 1 corresponds to the form factor $F_s(k^2)$ by formula (3), the curve 2 corresponds to $F_s(k^2) = \text{max}\{F_s(k^2)\} = 1.3$. Because of the gluon virtuality $k^2 \geq 4m_D^2$ is the same order as $Q_s^2$, the ratio $R_\Lambda$ strongly depends on the value of $Q_s^2$ as well as on the shape of the diquark form factor $F_s(k^2)$. Fig.2 demonstrates that the asymptotic behaviour of $R_\Lambda$ may be fixed at $\sqrt{s} > 15$ GeV.

We have found (Table 1), that the cross section for $\Sigma_b^\ast$-baryon pair production is larger than cross section for $\Lambda_b$-baryon pair production:

$$\sigma(\Sigma_b^\ast \Sigma_b^\ast)/\sigma(\Lambda_b \bar{\Lambda}_b) \approx 30 \text{ at } m_D = 0.6 \text{ GeV and } \sigma(\Sigma_b^\ast \Sigma_b^\ast)/\sigma(\Lambda_b \bar{\Lambda}_b) \approx 10 \text{ at } m_D = 0.9 \text{ GeV.}$$

Our results are in a qualitative agreement with the conclusions of Ref. [14], where the single charmed baryon production at CLEO energies have been calculated a similar way.

Taking into account that high spin heavy baryons decays into the ground state $\Sigma_b^\ast \rightarrow \Lambda_b + \pi$, we predict the large difference between direct and cascade $\Lambda_b \bar{\Lambda}_b$ pair production in $e^+e^-$-annihilation, which may be measured experimentally. We have estimated that the total cross section of the bottom baryon pair production in the $e^+e^-$-annihilation: $\sigma(\Lambda_b \bar{\Lambda}_b) + \sigma(\Sigma_b \bar{\Sigma}_b) + \sigma(\Sigma_b^\ast \bar{\Sigma}_b^\ast) = 1 - 16 \text{ pb at the different choice of the diquark mass.} \text{ We put here that } \sigma(\Sigma_b \bar{\Sigma}_b) = \sigma(\Sigma_b^\ast \bar{\Sigma}_b^\ast)/2.$

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Table 1

| Baryons   | $m_D$, GeV | $|R(0)|^2$, GeV$^2$ | $\sigma_{\text{max}}$, pb | $R_{\text{max}}$, % |
|-----------|------------|---------------------|-----------------|-----------------|
| $\Lambda_b\bar{\Lambda}_b$ | 0.6        | 0.73                | 0.36            | 0.23            |
| $\Sigma^*_b\Sigma^*_b$  | 0.6        | 0.73                | 11.0            | 6.4             |
| $\Lambda_b\bar{\Lambda}_b$ | 0.9        | 1.2                 | 0.05            | 0.03            |
| $\Sigma^*_b\Sigma^*_b$  | 0.9        | 1.2                 | 0.64            | 0.37            |

Figure captions

1. Diagrams used for description of the processes $e^+e^- \rightarrow \Lambda_b\bar{\Lambda}_b, \Sigma^*_b\Sigma^*_b$.

2. The ratio $R_A$ as a function of $\sqrt{s}$. The curver 1 corresponds to form factor $F_s(k^2)$ from [13], curver 2 corresponds to $F_s(k^2) = \max\{F_s(k^2)\} = 1.3$. 
\( \Sigma(p^-) \) \( \Lambda(p^-) \Sigma'(p) \)

\( \Lambda(p^-) \Sigma'(p) \)

FIG. 1. (1-2)
\[ e^{-i(p^0)} \rightarrow \Gamma_2(p^0, \Sigma^+(p) \rightarrow \Lambda_0(p), \Sigma^+(p) \rightarrow \Lambda_0(p), \Sigma^+(p') \]

\[ e^{-i(p^0)} \rightarrow \Gamma_3(p^0, \Sigma^+(p) \rightarrow \Lambda_0(p), \Sigma^+(p) \rightarrow \Lambda_0(p), \Sigma^+(p') \]

**FIG. 1.** (3-4)
