Λ_b POLARIZATION IN THE Z BOSON DECAYS.

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Abstract

In the framework of the perturbative QCD and the diquark model of baryons we have obtained the fragmentation functions for heavy quark that split into polarized Λ_b baryons. We predict the longitudinal polarization asymmetry for the prompt Λ_b produced in e^+e^- annihilation at the Z resonance and estimate the spin-1/2 and spin-3/2 beauty baryon production rate.

Introduction

The heavy baryon production in e^+e^- annihilation is an increasingly important subject to study. The recent measurements near the threshold of the heavy quark production, as well as at the Z resonance, give us the information about heavy baryon masses, life times, decay modes [1, 2, 3] and polarizations [4, 5].

The b quarks produced in e^+e^- annihilation at the Z peak are strongly polarized. Accordingly to the Standard Model the right-left longitudinal asymmetry is A_{RL}^b = -0.94. This polarization is expected [6] to be only slightly (2%) reduced by the hard gluon emission before the hadronization into baryons. Therefore the measurement of the Λ_b polarization is very important for study the details of the hadronization processes. The first measurement [4] gave an intriguingly small value A_{RL}^{Λ_b} = -0.23^{+0.26}_{-0.23}, which contradicts the prediction that the large part of the initial polarization of the quark to transfer to the Λ_b baryon.

The data on the Λ_b polarization may be described in part (A_{RL}^{Λ_b} ≈ -0.68) by means of a simple depolarization model, based on the cascade Λ_b partial production in the decays of higher spin beauty baryon produced in the Z decays [5].

In this paper we propose the depolarizing mechanism occurring during the prompt Λ_b production via b quark fragmentation. Our approach base on the perturbative QCD, the quark-diquark model of the baryons [8] and the nonrelativistic approximation, which is used successfully for the description of the large distance effects in the heavy quarkonium production [9]. The same approach have been discussed in the our previous paper [10], where the predictions for the doubly heavy baryon production via the heavy quark fragmentation have been presented.

1 The prompt Λ_b production in Z decays

The fragmentation function D_{b→Λ_b}(z,μ) at the initial scale μ = μ_o = m_Q + 2m_D for the production of the Λ_b baryon, containing the Q = b quark and the scalar diquark D = (ud),
is given by the following expression [10, 11]:

\[
D_{b \rightarrow \Lambda_b}(z, \mu_o) = \frac{1}{16\pi^2} \int_{s_{\text{min}}}^{\infty} ds \lim_{q_o \rightarrow \infty} \frac{|M|^2}{|M_o|^2},
\]

(1)

where \( M \) is the matrix element for the production \( \Lambda_b \) baryon and antidiquark \( \bar{D} \) with the total four-momentum \( q = p + q' \) and invariant mass \( s = q^2 \) in the \( Z \) decay \( (Z \rightarrow \Lambda_b \bar{D} \bar{b}) \), \( M_o \) is the matrix element for the production of a real \( b \) quark with the same three-momentum \( \bar{q}' \). The lower limit in the integral (1) is

\[
s_{\text{min}} = \frac{M^2}{z} + \frac{m_D^2}{1 - z},
\]

where \( M = m_Q + m_D \) is the baryon mass, \( m_Q \) is the heavy quark mass, \( m_D \) is the diquark mass.

The amplitude \( M_o \) may be presented as follows:

\[
M_o(Z \rightarrow b \bar{b}) = \bar{U}(p) \Gamma^\alpha V(\bar{q}) \varepsilon_\alpha(Z),
\]

(2)

where \( \varepsilon_\alpha(Z) \) is the polarization four-vector of the \( Z \) boson and

\[
\Gamma^\alpha = -\frac{ig}{2\cos \theta_W} \gamma^\alpha \left( C_V^b - C_A^b \gamma^5 \right)
\]

is the quark-boson vertex.

In the axial gauge for the gluon propagator associated with the four-vector \( n = (1,0,0,-1) \):

\[
d_{\alpha\beta}(k) = -g_{\alpha\beta} + \frac{k_\alpha n_\beta + k_\beta n_\alpha}{(kn)},
\]

the fragmentation contribution comes only from the Feynman diagram shown in Fig.1. After some obvious simplification we have obtained the matrix element of the \( Z \) decay into \( \Lambda_b \) baryon [14]:

\[
\mathcal{M}(Z \rightarrow \Lambda_b \bar{b} \bar{D}) = \frac{\Psi(0)}{\sqrt{2m_D^2}} g_s^2 \frac{4 \delta^{ij}}{3 \sqrt{3}} \frac{F_s(k^2)}{(s - m_Q^2)^2} \cdot 2\bar{U}(p) \left[ -M(\bar{q} + m_Q) + (s - m_Q^2) \left( \frac{n p}{n k} \right) \right] \Gamma^\alpha V(\bar{q}) \varepsilon_\alpha(Z)
\]

(3)

where \( g_s^2 = 4\pi \alpha_s, \ 4 \delta^{ij}/3 \sqrt{3} \) is the color factor of the diagram, \( F_s(k^2) \) is the form factor of the vertex \( g^* \rightarrow D \bar{D} \), \( \Psi(0) \) is the \( \Lambda_b = (QD) \) wave function at the origin in the quark-diquark approximation. The gluon coupling to scalar diquarks was used in the following form [8]:

\[
S^a_{\nu} = -i g_s T^a(q' - p_D)_\nu F_s(k^2),
\]

(4)

where \( T^a = \lambda^a/2 \) are Gell-Mann matrices, \( k = q' + p_D \) is the gluon four-momentum, the spinor \( \bar{U}(p) \) describes \( \Lambda_b \) baryon, \( p = p_Q + p_D, p_D = r p, p_Q = (1 - r)p, r = m_D/M \). The scalar diquark form factor at \( k^2 > 0 \) may be parameterized as in ref. [12], where the authors
fit successfully the angular distributions of the baryons in the processes $\gamma\gamma \rightarrow p\bar{p}, \Lambda\bar{\Lambda}$ and the widths of $J/\psi \rightarrow p\bar{p}, \Lambda\bar{\Lambda}$:

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

where $Q_s^2 = 3.22$ GeV$^2$ and form factor is restricted to value smaller than 1.3. We use also the parameterization (5) with the fixed full width at half maximum $\Gamma \approx 0.8$ GeV$^2$. In the both cases there are no singularities in the physical region of the virtuality of the fragmenting quark or the square of the gluon four-momentum.

The phenomenological diquark form factor parameterization (5) corresponds to the elastic vertex $g^* \rightarrow D\bar{D}$ [2]. However, in the fragmentation processes the contribution from the inelastic vertex $g^* \rightarrow D\bar{u}d$ may be dominant. There are no any information about inelastic diquark form factors. That is why we will use parameterization (5) to describe spin effects in the $\Lambda_b$ production. As it will be shown, the choice of the form factor parameterization is important only for the prediction the absolute values of the heavy baryon production rates, but the spin asymmetry doesn’t depend on a diquark form factor in the kinematic region, which is studied.

The reduced mass of the heavy quark – diquark system is the same order as one for the system of the two charmed quarks and we can hope that the calculation of the parameter $\Psi(0)$ using the potential approach, will be well-grounded and may be done with the quark-diquark interaction potential, which has been fixed previously in calculating the heavy baryon mass spectrum [3].

The energy distribution of the right (R) or the left (L) longitudinally polarized $\Lambda_b$ baryons produced in the $Z$ decays reduces at leading order in $\alpha_s$ to

$$\frac{d\Gamma_{R,L}^{Z \rightarrow \Lambda_b X}}{dz}(Z \rightarrow \Lambda_b X) = \Gamma(Z^0 \rightarrow b\bar{b})D_{b \rightarrow \Lambda_b}^{R,L}(z, \mu),$$

where

$$z = \frac{p_0 + p_3}{q_0 + q_3},$$

$p = (p_0, 0, 0, p_3)$ is 4-momentum of the $\Lambda_b$, $q = (q_0, 0, 0, q_3)$ is 4-momentum of the fragmenting b-quark and $\mu \approx m_Z/2$. Let us define

$$\Delta D_{b \rightarrow \Lambda_b}(z, \mu) = D_{b \rightarrow \Lambda_b}^R(z, \mu) - D_{b \rightarrow \Lambda_b}^L(z, \mu).$$

The unpolarized fragmentation function is

$$D_{b \rightarrow \Lambda_b}(z, \mu) = D_{b \rightarrow \Lambda_b}^R(z, \mu) + D_{b \rightarrow \Lambda_b}^L(z, \mu).$$

The longitudinal asymmetry $A_{\Lambda_b}^{RL}$ may be presented as follows:

$$A_{\Lambda_b}^{RL}(z, \mu) = \frac{\Delta D_{b \rightarrow \Lambda_b}(z, \mu)}{D_{b \rightarrow \Lambda_b}(z, \mu)}.$$
\[
\text{Tr} \left[ \bar{q} \gamma_5 \Gamma_\alpha \hat{q} \Gamma_\beta \right] \left( -g^{\alpha \beta} + Z^\alpha Z^\beta / m_Z^2 \right) = -2m_Z^2 C_Y C_A \left[ \frac{g^2}{4 \cos^2 \theta_W} \right].
\]  

(11)

Taking into account that the four-vector of the \( \Lambda_b \) polarization in the states with the different longitudinal polarization is \( R_{\lambda b} = \pm (p_3/M, 0, 0, p_0/M) \) and using the following exact formulae

\[
2pk = s - m_Q^2, \quad k^2 = r(s - m_Q^2),
\]
\[
2pq = s - m_Q^2 + 2M^2(1 - r), \quad 2Zq = m_Z^2 + s - m_Q^2,
\]

we can reduce the squared matrix elements to the form, which contains expressions (10) or (11).

Omitting the next details, we write here the obtained results for the unpolarized fragmentation function at the scale \( \mu = \mu_o \):

\[
D_{b \to \Lambda_b}(z, \mu_o) = D_o \int_{s_{\text{min}}}^{\infty} \frac{ds}{M^2} F_s^2(k^2) \left( \frac{M^2}{s - m_Q^2} \right)^4 \left[ d_o + d_1 \left( \frac{s - m_Q^2}{M^2} \right) + d_2 \left( \frac{s - m_Q^2}{M^2} \right)^2 \right],
\]

(12)

where

\[
D_o = \frac{32 \alpha_s^2 |\Psi(0)|^2}{27 r M^3},
\]

(13)

\[
d_o = 4(1 - r), \quad d_1 = \frac{1 - (4 - r)z - (1 - r)z^2}{1 - z(1 - r)} \quad \text{and} \quad d_2 = \frac{z^3}{(1 - z(1 - r))^2}.
\]

(14)

The result for the \( \Delta D_{b \to \Lambda_b}(z, \mu_o) \) may be written as for the \( D_{b \to \Lambda_b}(z, \mu_o) \) but we don’t present it here because of it’s unwieldy.

The recalculating of the fragmentation functions \( D_{\Lambda_b}^{RL}(z, \mu_o) \) from the start point \( \mu = \mu_o \) to the \( \mu > \mu_o \) may be done using Gribov-Lipatov-Altareli-Parisi (GLAP) evolution equations

\[
\mu \frac{\partial D}{\partial \mu}(z, \mu) = \int_x^1 \frac{dy}{y} P_{Q \to Q} \left( \frac{z}{y}, \mu \right) D(y, \mu),
\]

(15)

where \( P_{Q \to Q} \) is the splitting function at leading order in \( \alpha_s \):

\[
P_{Q \to Q}(x, \mu) = \frac{4 \alpha_s(\mu)}{3 \pi} \left( \frac{1 + x^2}{1 - x} \right)_+, \quad f(x)_+ = f(x) - \delta(1 - x) \int_0^1 f(x') dx'.
\]

(16)

Note that at leading order in \( \alpha_s \) one has

\[
\int P_{Q \to Q}(z, \mu) dz = 0,
\]

and the evolution equation implies that the fragmentation probability

\[
P_{b \to \Lambda_b} = \int D_{b \to \Lambda_b}(z, \mu) dz
\]
as well as the total asymmetry $A^b_{RL}$ don’t evolve with the scale $\mu$. However, the $z$-dependence of the $A^b_{RL}(z,\mu)$ changes drastically when the scale $\mu$ growth from $\mu = \mu_o$ to $\mu \approx m_z/2$.

First of all, we discuss here the results concerning spin effects in the prompt $\Lambda_b$ production, which don’t depend on the value of $\Psi(0)$. Figs. 2-4 demonstrate the dependence of the polarization asymmetry $A^b_{RL}$ on the diquark mass, the form factor parameterization, $z$ and QCD evolution scale $\mu$.

We can see in Fig.2 that $A^b_{RL} \neq A^b_{RL}$ at the realistic values of the diquark mass ($m_D = 0.6 - 0.9$ GeV corresponds to $|A^b_{RL}| = 0.90 - 0.87$) and only at the limit of $m_D \rightarrow 0$ one has $A^b_{RL} \approx A^b_{RL} = -0.94$. Our result corrects the assumption, which is used usually, that the $\Lambda_b$ baryon retain a large part of the initial polarization of the $b$ quark [14]. The predictions for the asymmetry as a function of $z$ strongly depends on the diquark mass at $\mu = \mu_o$, but at the large $\mu$ this dependence vanishes (Fig.3).

$A^\Lambda_{RL}(z,\mu)$ may be sensitive to the choice of the form factor parameterization at the small $\mu$ (see Fig.4), however at the scale $\mu = m_z/2$ the results corresponding the different form factor parameterizations are equal. The measurement of the $A^\Lambda_{RL}$ versus $z$ at the different $\mu$ is a exact test of the hadronization model. However, it may be done experimentally if we can to separate the prompt $\Lambda_b$ production in the $b$ quark fragmentation from the $\Lambda_b$ produced in the cascades: $b \rightarrow \Sigma^*_b\ldots$ plus the hadronical decays $\Sigma^*_b,\ldots \rightarrow \Lambda_b$. This opportunity was shown recently in the study of the heavy quarkonium production at FNAL [15], where the vertex detector technique was used.

The Figs.5 show our results for the $A^\Lambda_{RL}$ versus $z$ at the different $\mu = \mu_o, m_z/2$ and $m_D = 0.6$ GeV. We have obtained $A^\Lambda_{RL} = -0.58$ opposite to $A^\Lambda_{RL} = -0.67$. The probability of the heavy quark spin turning during the hadronization is about 13% for the $c$-quark and only 4% for the $b$-quark. The both values are independent from the diquark form factor and were obtained at $m_D = 0.6$ GeV. We see that the simple rule ($\sim m_D/m_Q$) is satisfied.

2 The cascade $\Lambda_b$ production in the $Z$ decays

Using the value of the radial part of the $\Lambda_b$ baryon wave function $|R(0)|^2 = 0.8$ GeV$^3$, ($\alpha_s = 0.4$, $m_D = 0.6$ GeV), which was calculated in the quark-diquark approximation [13], we have found the total probability of the $b$ quark fragmentation into the $\Lambda_b$: $P_{b \rightarrow \Lambda_b} \approx 2.5 \cdot 10^{-3}$ in the case of the form factor (5) and $P_{b \rightarrow \Lambda_b} \approx 2.5 \cdot 10^{-2}$ if the singularities are restricted using the fixed width $\Gamma$. In spite of this difference the shapes of the fragmentation functions $D_{b \rightarrow \Lambda_b}(z,\mu)$ are the same for the both form factors (Fig. 6). The obtained value $P_{b \rightarrow \Lambda_b}$ gives the number of $\Lambda_b$ per the $Z$ decay which is smaller than it was measured at LEP [3]. We conclude that the main part of the $\Lambda_b$ baryons are produced in the cascade processes via the decays of the higher spin $b$ baryons. The DELPHI collaboration has presented evidence for $\Sigma^*_b$ baryon production [14] and measured the rate to be $P_{b \rightarrow \Sigma^*_b} = 4.8 \pm 1.6\%$, the total $b$ baryon production rate to be $P_{b \rightarrow \text{baryon}} = 11.5 \pm 4.0\%$ [2].

We can estimate the fragmentation probability for the $b$ quark that split into $\Sigma^*_b$ baryon in our approach. However, as it was demonstrated in the case of the $\Lambda_b$ baryon production, the predicted absolute production rate is strongly depends on diquark form factor. It will be more reliable to calculate the ratio of the fragmentation probabilities for
the $b$ quark that split into vector diquark states to scalar diquark states, using deferent form factors. As it was shown in ref. [7] this parameter (called $A$) controls the $\Lambda_b$ polarization in the cascade production.

The gluon coupling to axial vector diquarks is presented by the following expression:

$$V^b_\mu = ig_s T^b \left\{ \varepsilon'^*_D (q' - p_D) \mu F_1(k^2) - [(q' \varepsilon_D)\varepsilon'^*_{D\mu} - (p_D \varepsilon^*_D)\varepsilon_D\mu] F_2(k^2) - (\varepsilon'^*_D q')(\varepsilon_D p_D)(q' - p_D)\mu F_3(k^2) \right\},$$

(17)

where $\varepsilon'^*_D, \varepsilon_D$ are the diquark polarization four-vectors. $F_1, F_2$ and $F_3$ are form factors depending on the momentum transfer squared $k^2 = (q' + p_D)^2$. The same as in ref. [12] we put for $k^2 > 0$:

$$F_1(k^2) = \left( \frac{Q_V^2}{Q_V^2 - k^2} \right)^2,$$

$$F_2(k^2) = (1 + \kappa) F_1(k^2), \quad F_3(k^2) = 0,$$

where $Q_V = 1.50 \text{ GeV}^2$ and $\kappa$ being the anomalous chromomagnetic moment of the vector diquark. The anomalous magnetic moment of the (ud) vector diquark was determined in ref. [12], but it is not obviously that the chromomagnetic and magnetic moments are equal. We will choose $\kappa = 0$ for the simplicity.

The amplitude for heavy quark fragmentation into spin-$3/2$ baryons, corresponding to fusion of the heavy quark and the axial vector diquark, can be written as a sum of two parts, which are proportional to $F_1$ and $F_2$ form factors:

$$\mathcal{M}_{3/2} = \mathcal{M}_{3/2}^1 + \mathcal{M}_{3/2}^2,$$

(19)

$$\mathcal{M}_{3/2}^1 = \frac{\Psi(0)}{\sqrt{2m_D}} g^2_s 4 \delta^{ij} F_1(k^2)$$

$$2\Psi_\mu(p_Q)\varepsilon_D\mu
\left[ -M(\bar{q} + m_Q) + (s - m_Q^2) \frac{(np)}{(nk)} \Gamma^{\alpha V}(\bar{q})\varepsilon_\alpha(Z),
\right]
$$

$$\mathcal{M}_{3/2}^2 = \frac{\Psi(0)}{\sqrt{2m_D}} g^2_s 4 \delta^{ij} F_2(k^2)$$

$$\frac{1}{r}\Psi_\sigma(p_Q)\varepsilon_D\lambda
\left[ q^\sigma \gamma^\lambda(\bar{q} + m_Q) + \frac{s - m_Q^2}{(kn)}(k^\lambda n^\sigma - k^\sigma n^\lambda) \right] \Gamma^{\alpha V}(\bar{q})\varepsilon_\alpha(Z).$$

Here, the $\bar{\Psi}_\mu(p)$ is the Rarita-Schwinger spinor for the spin-$3/2$ baryons. The procedure of the calculation for the fragmentation function $D_b \rightarrow \Sigma_b^*(z, \mu)$ is the same as for the $\Lambda_b$ baryons.

Using the set of parameters: $|R(0)|^2 = 0.8\text{GeV}^3$, $\alpha_s = 0.4$, $m_D = 0.6 \text{ GeV}$, $\kappa = 0$, we have found that the ratio $A$ of the fragmentation probabilities for the $b$ quark that split into vector diquark states to scalar diquark states is approximately equal to $5 \pm 1$.
independently on the choice of the diquark form factor. Accordingly the formula (5.10) ref.[7] one has

$$A_{\Lambda_b} = \frac{1 + (1 + 4w_1)A/9}{1 + A} A_{RL}^b,$$  \hspace{1cm} (22)

where the parameter $w_1$ gives the probability that spin-1 diquark has maximum angular momentum $j^3 = \pm 1$ along the fragmentation axis. The authors ref. [7] used $A = 0.45, \ w_1 = 0$, as it is motivated by the Lund fragmentation model [17], and obtained that $A_{RL}^b = -0.68$. If we put $A = 5$ in (22), as it follows from our results, we find that $A_{RL}^b = -0.24$ which is in a good agreement with the value of the measurement.

In conclusion we want note that the prediction of the cascade model [7] for the $A_{RL}^\Lambda_b$ in the Z decays was obtained using the assumption that the turning of the $b$ quark spin may be ignored, as is appropriate to the heavy quark approximation. Our results show that the probability of the $b$ quark overturning during the hadronization may equal to 4-7% and the more careful analysis of the depolarization in the cascade $\Lambda_b$ production is needed.

When our work was completed the result of the computing the heavy baryon production rates at CLEO and LEP energies, which was obtained a similar way, has been presented [18].

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Figure captions

1. Diagram used for description of the process $Z^o \to \Lambda_b \bar{b} \bar{D}$.

2. The asymmetry $A_{RL}^{\Lambda_b}$ as a function of the ratio $m_D/M$.

3. The asymmetry $A_{RL}^{\Lambda_b}$ as a function of $z$ at $\mu = \mu_o$ (curves 1 and 2) and $\mu = m_Z/2$ (curves 3 and 4). The solid lines correspond to $m_D = 0.9$ GeV, the dotted lines correspond to $m_D = 0.6$ GeV.

4. The asymmetry $A_{RL}^{\Lambda_b}$ as a function of $z$ at $m_D = 0.6$ GeV and $\mu = \mu_o$ (curves 1 and 2), $m_Z/2$ (curves 3 and 4). The solid lines correspond to diquark form factor parameterization (5), the dotted lines correspond to formula (5) with the fixed width $\Gamma = 0.8$ GeV$^2$.

5. The asymmetry $A_{RL}^{\Lambda_b}$ as a function of $z$ at $m_D = 0.6$ and $\mu = \mu_o$ (curve 1), $m_Z/2$ (curve 2).

6. The fragmentation function $D_{b \to \Lambda_b}(z, \mu)$ normalized to unity at $\mu = \mu_0$ (curves 1 and 2) and $\mu = m_Z/2$ (curves 3 and 4). The solid and dotted lines correspond to the different form factor parameterizations.
Figure 1: Diagram used for description of the process $Z^0 \to \Lambda_0 \bar{b} \bar{D}$. 
Figure 2: The asymmetry $A_{RL}^{A_b}$ as a function of the ratio $m_D/M$. 
Figure 3: The asymmetry $A_{RL}^{A_b}$ as a function of $z$ at $\mu = \mu_o$ (curves 1 and 2) and $\mu = m_Z/2$ (curves 3 and 4). The solid lines correspond to $m_D = 0.9$ GeV, the dotted lines correspond to $m_D = 0.6$ GeV.
Figure 4: The asymmetry $\Lambda_{R\Lambda}$ as a function of $z$ at $m_D = 0.6$ GeV and $\mu = \mu_o$ (curves 1 and 2), $m_Z/2$ (curves 3 and 4). The solid lines correspond to diquark form factor parameterization (5), the dotted lines correspond to formula (5) with the fixed width $\Gamma = 0.8$ GeV$^2$. 
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Figure 6: The fragmentation function $D_{b\to \Lambda_b}(z, \mu)$ normalized to unity at $\mu = \mu_0$ (curves 1 and 2) and $\mu = m_Z/2$ (curves 3 and 4). The solid and dotted lines correspond to the different form factor parameterizations.