Spin Effects in the Heavy Quark Fragmentation into Baryons

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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 splits directly into polarized Λ_b baryons.

The heavy baryon production is an increasingly important subject to study. The recent measurements give the information about heavy baryon masses, life times, decay modes [1, 2, 3] and polarizations [4, 5].

The b quarks produced in the Z-boson decay are strongly polarized. Accordingly to the Standard Model the right-left longitudinal asymmetry is $\mathrm{A}_{RL}^{b} = -0.94$. 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 the study of the details of the hadronization processes. The first measurement [4] gave an intriguingly small value $\mathrm{A}_{RL}^{\Lambda_b} = -0.23^{+0.26}_{-0.23}$, which contradicts the prediction that the large part of the initial polarization of the quark transfers to the Λ_b baryon.

The data on the Λ_b polarization may be described in part ($\mathrm{A}_{RL}^{\Lambda_b} \approx -0.68$) 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 [7].

In this paper we propose the depolarizing mechanism occurring during the prompt Λ_b production via b quark fragmentation. Our approach is based 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 our previous paper [10] (see also [11]), where the predictions for the doubly heavy baryon production via the heavy quark fragmentation have been presented.

At the initial scale $\mu = \mu_o = m_Q + 2m_D$ the fragmentation function $D_{b\to\Lambda_b}(z,\mu)$ 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, 12]:

$$D_{b\to\Lambda_b}(z,\mu_o) = \frac{1}{16\pi^2}\int_{s_{min}}^{\infty} ds \lim_{q_o\to\infty}\frac{|\mathcal{M}|^2}{|\mathcal{M}_o|^2}, \tag{1}$$

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

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

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 $\mathcal{M}_o$ may be presented as follows:

$$\mathcal{M}_o(Z \to b\bar{b}) = \bar{U}(q)\Gamma^\alpha V(\bar{q})\varepsilon_\alpha(Z), \tag{2}$$

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

$$\Gamma^\alpha = -\frac{ig}{2\cos\theta_W}\gamma^\alpha\left(\mathrm{C}_V^b - \mathrm{C}_A^b\gamma^5\right)$$

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 single Feynman diagram [10]. After some obvious simplification we have obtained the matrix element of the Z decay into Λ_b baryon [10]:

$$\mathcal{M}(Z \to \Lambda_b\bar{b}\bar{D}) = \frac{\Psi(0)}{\sqrt{2m_D}}g_s^2\frac{4\delta^{ij}}{3\sqrt{3}}\frac{F_s(k^2)}{(s-m_Q^2)^2}\cdot$$

$$2\bar{U}(p)\left[-M(\hat{q}+m_Q) + (s-m_Q^2)\left(\frac{np}{nk}\right)\right]\Gamma^\alpha V(\bar{q})\varepsilon_\alpha(Z) \tag{3}$$

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 $g^* \to D\bar{D}$, $\Psi(0)$ 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]:

$$S_\nu^a = -ig_s T^a (q' - p_D)_\nu F_s(k^2), \tag{4}$$

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 Λ_b baryon, $p = p_Q + p_D$, $p_D = rp$, $p_Q = (1-r)p$, $r = m_D/M$. The scalar diquark form factor at $k^2 > 0$ may be parameterized as in ref.[13], where the authors fit successfully the angular distributions of the baryons in the processes $\gamma\gamma \to p\bar{p}, \Lambda\bar{\Lambda}$ and the widths of $J/\psi \to p\bar{p}, \Lambda\bar{\Lambda}$:

$$F_s(k^2) = \frac{Q_s^2}{Q_s^2 - k^2}, \tag{5}$$

where $Q_s^2 = 3.22$ GeV^2 and form factor is restricted to value smaller than 1.3.

The reduced mass of the heavy quark–diquark system of the same order as one for the system of the two charmed quarks and we can hope that using the potential approach the calculation of the parameter $\Psi(0)$, will be well-grounded and may be done with the quark-diquark interaction potential, which has been fixed previously in calculation of the heavy baryon mass spectrum [14].

The energy distribution of the right (R) or left (L) longitudinally polarized Λ_b baryons produced in the Z decays in leading order in α_s reduces to

$$\frac{d\Gamma^{R,L}}{dz}(Z \to \Lambda_b X) = \Gamma(Z^o \to b\bar{b}) D^{R,L}_{b\to\Lambda_b}(z,\mu), \tag{6}$$

where $z = 2E_{\Lambda_b}/m_Z$ and $\mu \approx m_Z$. Let us define

$$\Delta D_{b\to\Lambda_b}(z,\mu) = D^R_{b\to\Lambda_b}(z,\mu) - D^L_{b\to\Lambda_b}(z,\mu). \tag{7}$$

The unpolarized fragmentation function is

$$D_{b\to\Lambda_b}(z,\mu) = D^R_{b\to\Lambda_b}(z,\mu) + D^L_{b\to\Lambda_b}(z,\mu). \tag{8}$$

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

$$\mathrm{A}^{\Lambda_b}_{RL}(z,\mu) = \frac{\Delta D_{b\to\Lambda_b}(z,\mu)}{D_{b\to\Lambda_b}(z,\mu)}. \tag{9}$$

Omitting the details, we write here the result for the unpolarized fragmentation function at the scale $\mu = \mu_o$:

$$D_{b\to\Lambda_b}(z,\mu_o) = D_o \int_{s_{min}}^{\infty} \frac{ds}{M^2} F_s^2(k^2) \left(\frac{M^2}{s - m_Q^2}\right)^4 \left[\mathrm{d}_o + \mathrm{d}_1 \left(\frac{s - m_Q^2}{M^2}\right) + \mathrm{d}_2 \left(\frac{s - m_Q^2}{M^2}\right)^2\right], \tag{10}$$

where

$$D_o = \frac{32{\alpha_s}^2 |\Psi(0)|^2}{27 r M^3}, \tag{11}$$

$$\mathrm{d}_o = 4(1-r), \quad \mathrm{d}_1 = \frac{1 - (4-r)z - (1-r)z^2}{1 - z(1-r)}, \quad \mathrm{d}_2 = \frac{z^3}{(1 - z(1-r))^2}, \tag{12}$$

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 do not present it here because of its complicated form.

The calculation of the fragmentation functions $D_{\Lambda_b}(z,\mu_o)$ from the start point $\mu = \mu_o$ to the $\mu > \mu_o$ may be done using Gribov-Lipatov-Altareli-Parisi (GLAP) evolution equations. Note that at the leading order in α_s the evolution equation implies that the fragmentation probability as well as the total asymmetry $\mathrm{A}^{\Lambda_b}_{RL}$ do not evolve with the scale μ. However, the $z-$dependence of the $\mathrm{A}^{\Lambda_b}_{RL}(z,\mu)$ changes drastically when the scale μ grow from $\mu = \mu_o$ to $\mu \approx m_Z/2$.

We must note that the results concerning spin effects in the prompt Λ_b production do not depend on the value of $\Psi(0)$. Figs. 1 and 2 demonstrate the dependence of the polarization asymmetry $A_{RL}^{\Lambda_b}$ on the diquark mass, z and QCD evolution scale μ.

We can see in Fig.1 that $A_{RL}^{\Lambda_b} \neq A_{RL}^{b}$ at the realistic values of the diquark mass ($m_D = 0.6 - 0.9$ GeV corresponds to $|A_{RL}^{\Lambda_b}| = 0.90 - 0.86$) and only at the limit of $m_D \to 0$ one has $A_{RL}^{\Lambda_b} \approx A_{RL}^{b} = -0.94$. Our result corrects the assumption that the Λ_b baryon retain a large part of the initial polarization of the b quark [15]. The predictions for the asymmetry as a function of z strongly depends on the diquark mass at $\mu = \mu_o$, but at the large μ this dependence vanishes (Fig.2).

The measurement of the $A_{RL}^{\Lambda_b}$ versus z at the different μ is an exact test of the hadronization model. Howere, it may be done experimentally if we can separate the prompt Λ_b production in the b quark fragmentation from the Λ_b produced in the cascades: $b \to \Sigma_b^*, ...$ plus the hadronic decays $\Sigma_b^*, ... \to \Lambda_b$. This opportunity was shown recently in the study of the heavy quarkonium production at FNAL [16], where the vertex detector technique was used.

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Fig. 1 The asymmetry $A_{RL}^{\Lambda_b}$ as a function of the ratio m_D/M.

Fig. 2 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.