Note on the baryonic $B \to \bar{\Lambda} p \eta'$ decay

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In this short report we examine the exclusive three-body $B \to \bar{\Lambda} p \eta'$ decay using a simple pole model involving a scalar intermediate resonance state. Our aim is to test the recently formulated hypothesis that charmless baryonic B decays could occur mainly in association with η' or γ.

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In a recent paper by Hou and Soni [1], the general problem of searching for new ways to estimate charmless baryonic B decays was addressed. The thesis is that charmless baryonic B decays may be more prominent in association with η' or γ. In particular, attention is focused on the exclusive process $B \to \eta' \bar{\Lambda} p$, taking the cue from the experimental observation of the unexpectedly large modes $B \to \eta' X_s$ and $B \to \eta' K$ [2].

Since the enhancement $[Br(B \to \eta' K) \simeq 8 \times 10^{-5}]$ was established by the CLEO Collaboration, many studies aimed at investigating its nature have appeared. An interesting proposal to explain the phenomenon is that based on the subprocess $b \to s g^* \to s \eta' g$, where the virtual gluon g^* emerging from the standard model penguin amplitude couples to η' via an effective $g g^* \eta'$ vertex related to the gluonic triangle anomaly [3]. The structure of this vertex was reexamined in Ref. [4], where the running of the effective coupling of η' to gluons, assumed to be constant in Ref. [3], was also taken into account. The possibility that the $g g^* \eta'$ vertex could be dangerously affected by out of control nonperturbative effects was discussed in Ref. [5]. Some further criticism can be found in Ref. [6]. The emergence of a $g^* g \eta'$ coupling in the $B \to D \eta'$ decay has been explored in Ref. [7]. In Ref. [8] a "nonspectator model" has been introduced to study the inclusive $B \to \eta' X_s$ and the exclusive $B \to K^{(*)} \eta'$ decays: the gluon g of the $g g^* \eta'$ vertex is supposed to be emitted by the light quark inside the B meson, while the g^* comes from the $b \to s$ penguin amplitude.

Taking advantage of the latter mechanism, we estimate the $B \to \eta' \bar{\Lambda} p$ branching ratio using a simple pole model according to which this decay proceeds via an intermediate *scalar* meson. A pole model is also used in Ref. [1] to gain a quantitative estimate of $B \to \eta' \bar{\Lambda} p$, but the intermediate state there assumed is a K meson which makes the pole approximation questionable because the K is clearly quite off its mass shell. As already noted in [1] it would be preferable to exploit the idea of a g^* emerging from the penguin amplitude and fragmenting into a diquark pair rather than rely on the simple picture of an intermediate state mediating the baryonic decay. The former approach takes care of the short distance dynamics which is instead completely lost when considering only the long distance contribution due to the intermediate state. Diquark models and sum rules are certainly the most complete approaches to baryonic decays (see the discussion in [9], see also [10]), anyway, in many cases, simple pole ideas have provided reasonable estimates of several exclusive processes.

In this report we will consider a pole model of the $B \to \eta' \bar{\Lambda} p$ interaction involving as intermediate meson state the $K_0^*(1430)$ scalar resonance [11]; in other words we will assume that the decay proceeds as follows $B \to \eta' K_0^* \to \eta' \bar{\Lambda} p$. The effective couplings $K \bar{\Lambda} p$ and $K_0^* \bar{\Lambda} p$ have been computed in Ref. [12] in the framework of a nuclear-soft-core model. It is interesting to observe that the latter coupling is suggested to be almost ten times bigger than the former (see Tables VI and VII in Ref. [12]), suggesting that the $K_0^*(1430)$ state is a quite better candidate for being considered as the intermediate state in $B \to \eta' \bar{\Lambda} p$.

The diagram we consider is shown in Fig. 1 while in Fig. 2 we show the diagram supposed to be responsible for the η' coupling to the B meson [8]. The penguin interaction and the $\eta' gg$ vertices are depicted effectively as two black spots, while the interaction of the almost-on-shell gluon (carrying momentum p) with the light quark line is represented with a smaller spot. This "nonspectator mechanism" has been used in Ref. [8] to predict the $Br(B \to K \eta')$ branching ratio. In this report we merely use the model to fit $B \to K \eta'$ and afterwards to predict $B \to K_0^* \eta'$. Once the $B K_0^* \eta'$ coupling is known, using the pole model we estimate the $Br(B \to \eta' \bar{\Lambda} p)$ with the Breit-Wigner approximation for the intermediate K_0^*.

The effective $\eta' gg$ vertex is given by

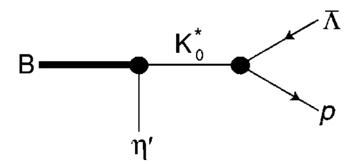

FIG. 1. The $B \to \bar{\Lambda} p \eta'$ decay is modeled to proceed via the intermediate scalar resonance $K_0^*(1430)$. With respect to the calculation sketched in Ref. [1], where K is taken in place of K_0^*, here we are considering the more reliable case in which the intermediate state is not heavily off its mass shell. Moreover, the effective coupling of $K_0^* \bar{\Lambda} p$, calculated in Ref. [9], is definitely stronger than that of $K \bar{\Lambda} p$.

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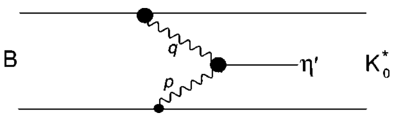

FIG. 2. According to the model used, η' is coupled to the virtual gluon produced in the SM $b\to s$ penguin amplitude and the soft gluon radiated by the light quark in the B.

$$A^{\mu\sigma}(gg\to\eta')=iH(q^2,p^2,m_{\eta'}^2)\epsilon^{\mu\sigma\alpha\beta}q_\alpha p_\beta, \tag{1}$$

where the form factor $H(0,0,m_{\eta'}^2)$ is estimated to be approximately 1.8 GeV^{-1} [3]. Here we consider the q^2 dependence of H described in Ref. [13] (see Fig. 13 in Ref. [13]), where $q^2=m_{\eta'}^2+2p_0E_{\eta'}$ (see Fig. 2). Our starting point is the expression for the amplitude of $B\to K\eta'$ obtained in Ref. [8]:

$$\begin{aligned}\langle\eta' K|H_{\rm eff}|B\rangle&=-i\frac{2CHf_Bf_K}{9\Lambda^2}\\&\quad\times(p_B\cdot q p_K\cdot p-p_B\cdot p p_K\cdot q)\\&=-i\frac{2CHf_Bf_K}{9\Lambda^2}m_Bp_0\\&\quad\times\left[(m_B-E_K)E_K-\frac{(m_B^2-m_\eta^2-m_K^2)}{2}\right],\end{aligned}\tag{2}$$

where

$$H_{\rm eff}=iCH[\overline{s}\gamma_\mu(1-\gamma_5)T^ab](\overline{q}\gamma_\sigma T^aq)\frac{1}{p^2}\epsilon^{\mu\sigma\alpha\beta}q_\alpha p_\beta. \tag{3}$$

The latter equation is a combination of Eq. (1) and of the flavor changing vertex $b\to sg$ [14], according to the model in Fig. 2. The second factor is the qqg vertex, q being the light quark in the heavy meson. The C constant is built with the Inami-Lim function E [14] according to

$$C=\frac{G_F}{\sqrt{2}}\frac{\alpha_s}{2\pi}V_{tb}V_{td}^*[E(x_t)-E(x_c)], \tag{4}$$

where

$$\begin{aligned}E(x_i)&=-\frac{2}{3}\ln(x_i)+\frac{x_i^2(15-16x_i+4x_i^2)}{6(1-x_i)^4}\ln(x_i)\\&\quad+\frac{x_i(18-11x_i-x_i^2)}{12(1-x_i)^3},\end{aligned}\tag{5}$$

$x_i=m_i^2/m_W^2$, m_i being the internal quark mass and we assume $\alpha_s=0.2$, $f_B=0.2$ GeV, and $f_K=0.167$ GeV.

The second equation in Eq. (2) is obtained in the center of mass frame of the decaying B and averaging on the directions of the gluon radiated by the light quark in the B system (see Fig. 2). Obviously

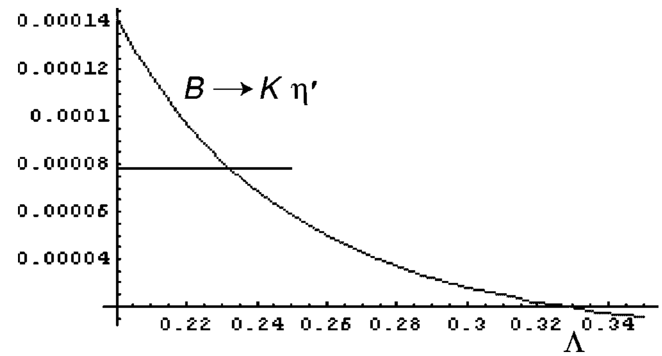

FIG. 3. In the nonspectator model there is an important dependence on the cutoff Λ chosen. In our case we use Λ just as a fit parameter. We fit the $B\to K\eta'$ to predict $B\to K_0^*\eta'$. The experimental value indicated by the horizontal line selects $\Lambda=0.23$ GeV.

$$\begin{aligned}E_K&=\sqrt{m_K^2+\mathbf{p}_K^2},\\|\mathbf{p}_K|&=\left[\frac{m_B^2+m_K^2-m_{\eta'}^2}{4m_B^2}-m_K^2\right]^{1/2}.\end{aligned}\tag{6}$$

Assuming the cutoff $\Lambda=0.23$ GeV in Eq. (2) ($\Lambda\approx\Lambda_{\rm QCD}$), and considering also p_0, the energy of the almost-on-shell gluon emitted softly by the light quark, $p_0\approx\Lambda$, we reproduce fairly well the experimentally observed central value of $Br(B\to K\eta')=7.8\times10^{-5}$.

Having fitted the parameter Λ (see Fig. 3) on the observed rate for $B\to K\eta'$, once p_0 is chosen to be $p_0\simeq0.25$ GeV, we can now consider the case of the $B\to K_0^*\eta'$ process writing, after Ref. [8], the expression for its amplitude as

$$\begin{aligned}\langle\eta' K_0^*|H_{\rm eff}|B\rangle&=+i\frac{2CHf_Bf_{K_0^*}}{9\Lambda^2}\\&\quad\times(p_B\cdot q\ \ p_{K_0^*}\cdot p-p_B\cdot p p_{K_0^*}\cdot q).\end{aligned}\tag{7}$$

We take the definition and the value of the leptonic decay constant $f_{K_0^*}$ in Ref. [15]:

$$f_{K_0^*}m_{K_0^*}^2=0.0842\pm0.0045\ \ \mathrm{GeV}^3. \tag{8}$$

Using the amplitude given in Eq. (7) we readily compute the branching ratio:

$$Br(B\to K_0^*\eta')=3.4\times10^{-6}. \tag{9}$$

To perform this estimate we use a value for the H form factor given by $H=1.5$ GeV^{-1} instead of the $H(0,0,m_{\eta'}^2)=1.8$ GeV^{-1}. This is because we take into account the form factor suppression extensively described in Ref. [13] (see Fig. 13 of Ref. [13]).

The latter prediction is functional to compute the Br for the process $B\to\overline{\Lambda}p\eta'$ using the coupling

$$\frac{g^{(\mathrm{eff})}_{K_0^*\Lambda p}}{\sqrt{4\pi}} = -2.83, \tag{10}$$

computed in Ref. [12]. (In Ref. [12] the symbol κ is used rather than K_0^*; see Ref. [16]). The expression for the width is given by

$$\begin{aligned}\Gamma(B\to\overline{\Lambda}p\,\eta')_{K_0^*} = & \frac{G_1G_2}{16(2\pi)^3 m_B^3} \\ & \times\int_{(m_\Lambda+m_p)^2}^{(m_B-m_{\eta'})^2} dq^2\lambda^{1/2}(m_B^2,q^2,m_{\eta'}^2) \\ & \times\frac{1}{(m_{K_0^*}^2-q^2)^2+\Gamma_{K_0^*}^2 m_{K_0^*}^2}\,\frac{1}{q^2} \\ & \times\lambda^{1/2}(q^2,m_\Lambda^2,m_p^2),\end{aligned} \tag{11}$$

where G_2 and G_1 are, respectively, $4\pi(g^{(\mathrm{eff})}_{\kappa\Lambda p})^2$ and $|\langle\eta' K_0^*|H_{\mathrm{eff}}|B\rangle|^2$. The λ function is the Källén triangular function defined as $\lambda(x,y,z)=x^2+y^2+z^2-2(xy+yz+xz)$. This appears in the integrated two-body phase space for a spinless decaying particle a:

$$\Gamma(a\to b+c) = \frac{1}{16\pi m_a^3}\lambda^{1/2}(m_a^2,m_b^2,m_c^2)|g_{abc}|^2, \tag{12}$$

g_{abc} being the matrix element of the process at hand. The couplings $BK_0^*\eta'$ and $B(K_0^*)_{\mathrm{off}\text{-}shell}\eta'$ are assumed to be the same and the Breit-Wigner formula is implemented. Equation (11) allows for a prediction of the branching ratio:

$$Br(B\to\overline{\Lambda}p\,\eta') = 6.0\times10^{-7}, \tag{13}$$

which is sensibly lower than what was expected in Ref. [1], namely $Br(B\to\overline{\Lambda}p\,\eta')=2.4\times10^{-5}$. Varying smoothly the value of p_0 and selecting accordingly the value of the form factor H from Ref. [13] and the value of the cutoff Λ in order to fit $B\to K\eta'$, we find a nice stability of the Br obtained in Eq. (13). Even more stable against variation of the parameters is the value of $Br(B\to\eta' K_0^*)$. It is worth noting that $\Gamma(B\to\overline{\Lambda}p\,\eta')_{K_0^*}/\Gamma(B\to K_0^*\eta')\simeq 0.18$. However, it should be stressed that, due to the intrinsic model dependence of our approach and due to the complexity of the baryonic decays, these results have to be understood as order-of-magnitude estimates. Interestingly, what emerges here is that a simple pole model, suggests a quite reasonable rate for a charmless baryon-antibaryon final state produced in association with η' in a B decay.

This exclusive mode could be soon reconstructed by the BaBar and Belle Collaborations and our straightforward calculation provides the possibility to test the nonspectator model in Ref. [8], the nuclear-soft-core model in Ref. [12] and, more basically, the anomaly picture in Ref. [3].

Once observed, B meson baryonic modes could also offer new paths to explore fundamental topics such as the extraction of CP violating phases.

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