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

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In this short note we examine the exclusive three-body $B \to \bar{\Lambda} p \eta'$ decay using a simple pole model involving a scalar intermediate resonance state. We find that this channel could be quite sizeable in agreement with the recently formulated hypothesis that charmless baryonic $B$ decays could occur mainly in association with $\eta'$ or $\gamma$.

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In a recent paper by Hou and Soni [1], the general problem of searching new ways to estimate charmless baryonic $B$ decays is addressed. The thesis is that charmless baryonic $B$ decays may be more prominent in association with $\eta'$ or $\gamma$. In particular, the attention is posed 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 $b \to sg' \to sg'g$, where the virtual gluon $g'$ emerging from the standard model penguin couples to $\eta'$ via an effective $gg'\eta'$ 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 $\eta'$ to gluons, assumed to be constant in ref. [3], is also taken into account. The possibility that the $gg'\eta'$ 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 ‘non-spectator model’ involving a gluon fusion process 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 $gg'\eta'$ vertex is supposed to be emitted by the light quark inside the $B$ meson, while the $g^*$ comes from the $b \to s$ penguin.

Taking advantage from 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 used also 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 it’s already noted in [1] it would be preferable to exploit the idea of a $g^*$ emerging from the penguin 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 note 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 $K_0^*$ state is a quite better candidate for being considered as the intermediate state in $B \to \eta' \bar{\Lambda} p$.

In Fig. 1 it is shown the diagram we are considering while in Fig. 2 we report the gluon fusion mechanism supposed to be responsible for the $\eta'$ 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 ‘non-spectator-mechanism’ has been used in ref. [8] to predict the $Br(B \to K\eta')$ branching ratio. In this note we merely use the model to fit $B \to K\eta'$ and afterwards to predict $B \to K_0'^*\eta'$. Once the $BK_0'^*\eta'$ 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:

$$A_\alpha^\mu(q \to \eta') = iH(q^2, p^2, m_\eta'^2)\epsilon_{\mu\rho\sigma\beta}q_{\rho}p_{\beta},$$  \hspace{1cm} (1)

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where the form factor $H(0, 0, m_{q_f}^2)$ 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 $q^2 = m_{q_f}^2 + 2p_0 E_{q'}$ (see Fig. 2). Our starting point is the expression for the amplitude of $B \to K \eta'$ obtained in ref. [8]:

$$
\langle \eta' | H_{\text{eff}} | B \rangle = -i \frac{2CHf_B f_K}{9\Lambda^2} (p_B \cdot q p_K \cdot p - p_B \cdot p p_K \cdot q) 
$$

$$
= -i \frac{2CHf_B f_K}{9\Lambda^2} m_B p_0 \left[ (m_B - E_K)E_K - \frac{(m_B^2 - m_q^2 - m_K^2)}{2} \right],
$$

where:

$$
H_{\text{eff}} = iCH(\bar{s}\gamma_\mu(1 - \gamma_5)T^a b)(q\gamma_\alpha T^a q) \frac{1}{p^2} \epsilon^{\mu\sigma\alpha\beta} q_{\alpha} p_{\beta}.
$$

The $C$ constant is built with the Inami-Lim function $E$ [14] according to:

$$
C = \frac{G_F \alpha_s}{\sqrt{2}} \frac{1}{2\pi} V_{tb} V_{td}^* [E(x_i) - E(x_c)],
$$

where:

$$
E(x_i) = -\frac{2}{3} \ln(x_i) + \frac{x_i^2(15 - 16x_i + 4x_i^2)}{6(1 - x_i)^4} \ln(x_i)
$$

$$
+ \frac{x_i(18 - 11x_i - x_i^2)}{12(1 - x_i)^3},
$$

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

$$
E_K = \sqrt{m_K^2 + p_K^2}
$$

$$
|p_K| = \left[ \frac{m_B^2 + m_K^2 - m_q^2}{4m_B^2} - m_K^2 \right]^{1/2}.
$$

Assuming the cutoff $\Lambda = 0.23$ GeV in (2) ($\Lambda \approx \Lambda_{QCD}$), 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 $Br(B \to K \eta') = 7.8 \times 10^{-5}$.

Having fitted the parameter $\Lambda$ (see Fig. 3) on the observed rate for $B \to K \eta'$, once $p_0$ is chosen to be $p_0 \approx 0.25$ GeV, we can now consider the case of the $B \to K_0^\ast \eta'$ process writing, after ref. [8], the expression for its amplitude as:

$$
\langle \eta' K_0^\ast | H_{\text{eff}} | B \rangle = +i \frac{2CHf_B f_{K_0^\ast}}{9\Lambda^2} (p_B \cdot q p_{K_0^\ast} \cdot p - p_B \cdot p p_{K_0^\ast} \cdot q).
$$

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

$$
f_{K_0^\ast} = 0.0842 \pm 0.0045 \text{ GeV}^3.
$$

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

$$
Br(B \to K_0^\ast \eta') = 3.4 \times 10^{-6}.
$$

To perform this estimate we use a value for the $H$ form factor given by $H = 1.5 \text{ GeV}^{-1}$ instead of the $H(0, 0, m_{q_f}^2) = 1.8 \text{ GeV}^{-1}$. 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 $B \to \bar{A} p \eta'$ using the coupling
computed in ref. [12]. (In ref. [12] it is used the symbol χ rather than \( K_0^* \); see note [16]). The expression for the width is given by:

\[
\Gamma(B \to \Lambda \eta') = \frac{G_1 G_2 m_{K_0^*}}{8 m_B} \times \int_{(m_\pi^2 + m_\eta^2)^2}^{(m_B^2 - m_{\eta'}^2)^2} dq^2 \lambda^2 (m_B^2, q^2, m_{\eta'}^2) \frac{1}{m_{K_0^*}^2 - q^2 + \Gamma_{K_0^*}^2} \frac{1}{m_{K_0^*}^2} \lambda^2 (q^2, m_\Lambda, m_{\eta'}^2), \tag{11}
\]

where \( G_2 \) and \( G_1 \) are respectively 4\( \pi (g_{\eta' \Lambda \eta}^{\text{eff}})^2 \) and \(|\langle \eta' K_0^* | H_{\text{eff}} | B \rangle|^2 \). The couplings \( BK_0^* \eta' \) and \( B(K_0^*)_{\text{eff-shell}} \eta' \) are assumed to be the same and the Breit-Wigner formula is implemented. Eq. (11) allows for a prediction of the branching ratio:

\[
Br(B \to \Lambda \eta') = 1.7 \times 10^{-4}, \tag{12}
\]

which is sensibly higher than what expected in ref. [1], namely \( Br(B \to \Lambda \eta') = 2.4 \times 10^{-5} \). 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 \( \Lambda \) in order to fit \( B \to K\eta' \), we find a nice stability of the \( Br \) obtained in eq. (12). Even more stable against variation of the parameters is the value of \( Br(B \to \eta' K_0^*) \). It is worth noting that using the effective coupling \( g_{\eta' \Lambda \eta}^{\text{eff}} / \sqrt{4\pi} = -0.33 \) and the analog of eq. (11) for the pseudoscalar intermediate state, we obtain \( \Gamma(B \to \Lambda \eta') / \Gamma(B \to K \eta') \approx 0.1 \), while in ref. [1] a value of 0.3 is estimated (by means of eq. (11) we recover this latter 0.3 prediction for the width ratio if we assume the effective coupling constant used in [1] and deduced on the basis of \( SU_3 \) flavour arguments). 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, more solid than the one sketched in ref. [1], suggests a quite sizeable rate for a charmless baryon-antibaryon final state produced in association with \( \eta' \) 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 non-spectator 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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The $\kappa$ state has actually the same quantum numbers as $K^*_0(1430)$ except for the mass which is taken to be 1300 MeV in the paper by Stocks and Rijken [12]. One can take into account this mass difference by considering a 10% variation in the value of the effective coupling.

\begin{figure}
\centering
\includegraphics[width=0.5\textwidth]{fig1}
\caption{The $B \to \Lambda p \eta'$ decay is modeled to proceed via the intermediate scalar resonance $K^*_0(1430)$. With respect to the calculation sketched in ref. [1], where the $K$ 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 $K^*_0 \Lambda p$ as predicted in ref. [9] is definitely stronger than that of $K \Lambda p$.}
\end{figure}

\begin{figure}
\centering
\includegraphics[width=0.5\textwidth]{fig2}
\caption{According to the non-spectator-model the $\eta'$ is produced via the gluon fusion of the virtual gluon produced in the SM $b \to s$ penguin and the soft gluon radiated by the light quark in the $B$.}
\end{figure}

\begin{figure}
\centering
\includegraphics[width=0.5\textwidth]{fig3}
\caption{In the non spectator model there is an important dependence on the cutoff $\Lambda$ chosen. In our case we use $\Lambda$ 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.}
\end{figure}