Final state interaction enhancement effect on the near threshold $p\bar{p}$ system in $B^{\pm} \rightarrow p\bar{p}\pi^{\pm}$ decay

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We discuss the low-mass enhancement effect in the baryon-antibaryon invariant mass in three-body baryonic $B$ decays using final state interactions in the framework of Regge theory. We show that the rescattering between baryonic pair can reproduce the observed mass spectrum.

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I. INTRODUCTION

The mesonic $B$ decays have been intensively studied principally to test Standard Model and to investigate the CP violation mechanism as predict by the Cabibbo-Kobayashi-Maskawa model. On the other hand, the large mass of the $b$-quark allows $B$ meson to decay into a pair baryon–antibaryon too. The first measurements of baryonic $B$ decays were reported by ARGUS collaboration [1], at the end of ‘80 years, and stimulated extensive theoretical studies. Interest in this area was revitalized in the last years thanks to the new measurements collected by CLEO, BELLE and BaBar. The phenomenology of baryonic $B$ decays is rich and diversified (for recent reviews see Ref.[2–4]): in this paper we will refer to three-body $B$ decays with a baryon-antibaryon pair and a meson in the final state.

There is a common and unique feature for baryon–antibaryon–meson $B$ decays, to which this paper is devoted, that is the observed peak, near to the threshold area, in the invariant mass spectrum of baryon-antibaryon system. The first experimental observation of this enhancement came from Belle collaboration studying the proton-antiproton system for the decays $B \rightarrow p\bar{p}K$ [5] and $B \rightarrow p\bar{p}D^{(*)}$ [6]. Very recently BaBar collaboration confirmed the threshold enhancement in the same channels [7, 8] with a very high statistics. Next the same peak has been found by BELLE studying the channels $B \rightarrow p\bar{p}\pi$ and $B \rightarrow p\bar{p}K^*$ [9]; these results are reported in Fig. 1.

The low-mass enhancement effect in three-body baryonic $B$ decays indicates, thus, that there is a favorable experimental configuration, the baryon-antibaryon pair with low invariant mass accompanied by a fast recoil meson, that is preferred respect to the other. Therefore, the main consequence of the threshold effect is that the two-body baryonic decays, which have an invariant mass fixed to $m_B$, should be disfavored respect to three-body decays. In fact it has

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{Experimental results for $B^{+} \rightarrow p\bar{p}\pi^{+}$ and $B^{+} \rightarrow p\bar{p}K^{*+}$ respectively on the left and right panel. The shared distribution is from the phase-space MC simulation with area normalized to signal yield [9]. In both cases is evident the sharp peak near to $m_{p\bar{p}} \approx 2m_p \approx 2$ GeV.}
\end{figure}

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been well established experimentally that
\[ B(B \to B\bar{B}M) \gg B(B \to B\bar{B}') : \]
\[ B(B \to B\bar{B}M) \approx O(10^{-6}) \text{ and } B(B \to B\bar{B}') \approx O(10^{-7}) \] [2–4]. In other words, thanks to the threshold effect, in \( B \to B\bar{B}M \) decays the effective mass of baryon-antibaryon is reduced, respect to the baryonic two-body decays, as the emitted meson carries away much energy. The hierarchy on the Branching ratio in (1) is thus an indirect support to the enhancement effect.

Several theoretical speculations have been proposed to interpret the anomalous observed peak at the threshold. The first discussion was given by Hou and Soni using a simple pole model [16], and subsequently this mechanism has been addressed in the QCD naive-factorization approach [17, 18]. Various interpretations include models with baryon-antibaryon bound state based on the old idea of Fermi and Yang [19], while exotic interpretations are given in terms of glueball intermediate states and fragmentation picture as in Ref. [20]. Furthermore, the problem has been studied also in the framework of perturbative QCD: in this scheme the enhancement is led back to the asymptotic behaviour of baryonic form factors [21].

In this paper we will follow a different philosophy. The threshold enhancement effect in proton-antiproton invariant mass, is not an exclusive prerogative of \( B \) meson decay but it has been observed also in other meson decays, with a very similar behavior: in the \( J/\psi \to \gamma p\bar{p} \) decay by BES collaboration [10] and from CLEO measurements in \( \Upsilon(1S) \to \gamma p\bar{p} \) decay [11]. Furthermore, recent observations made at the LEAR at CERN, studying the proton-antiproton production in the cross section of the reaction \( e^+e^- \to p\bar{p} \) [12], showed a near threshold structure similar to the previous one. Moreover the characteristic near threshold enhancement is not only present in the proton-antiproton system but also in the systems that contain hyperons as \( \Lambda \bar{p} \) and \( \bar{\Lambda}p \), as observed by BELLE in \( B_0 \to p\bar{\Lambda}\pi^- \) decay [13] and by BES in \( J/\psi \to p\bar{\Lambda}K^- + c.c. \) decay [14], and in the system \( \Lambda\bar{\Lambda} \) as observed by BELLE in \( B^+ \to \Lambda\bar{\Lambda}K^+ \) decay [15].

As one can see from the list of experimental data, the enhancement effect is universal and it is present with similar feature in different contexts: \( B \) decays as well as \( J/\psi \) and \( \Upsilon \) decays, it is found in the \( p\bar{p} \) system as well as in \( \Lambda\bar{p} \) system etc. Therefore these experimental results suggest that:

\begin{quote}
the low-energy enhancement in baryon-antibaryon mass spectrum is mostly related with the dynamics of the baryonic pair and is weakly depending by the production decay vertex.
\end{quote}

For this reason we consider the threshold enhancement effect in decays as \( B \to B\bar{B}M \) is due to the interactions in the baryon-antibaryon system. We will return on this hypothesis in Section III. Rescattering effect have been studied, in \( B \) decays as well as in \( J/\psi \) decays, in some recent papers based on potential-like model for baryon-antibaryon interaction (Paris or Bonn potential) or by using one-pion-exchange model (OPE) [22–24]. In this paper we address the final state interactions in the framework of Regge theory, in particular we will study in detail the channel \( B \) into \( p\bar{p}\pi \).

## II. FINAL STATE INTERACTIONS FOR THREE-BODY DECAYS

In this section we write some basic formula for final state interactions model, in the formalism of Regge theory [25], for three-body decays. In particular we study in detail \( B \to p\bar{p}\pi \). We start to define the kinematic variables as

\[ s = (p_p + p_{\bar{p}})^2, \quad x = (p_p + q)^2, \quad y = (p_{\bar{p}} + q)^2, \]

respectively the invariant mass of proton-antiproton, proton-pion and antiproton-pion system; they satisfy the constraint \( s + x + y = m_B + 2m_p + m_\pi \). In the following we neglect the pion mass respect to the other ones and we work

\[  \text{FIG. 2: Final state interactions for three-body decay. Definition of kinematic variables.} \]
with $s$ and $x$ as independent variables. The relation between the 'full' amplitude $A$, where the final state interactions are take into account, and the 'bare' amplitude $\tilde{A}$ is given by the Watson–Migdal theorem [26]:

$$A = \sqrt{s} \tilde{A},$$

(3)

where $S$ is the rescattering strong interaction $S$-matrix for a given partial wave $(J = 0$ in the present case). In the following we consider rescattering without flavour changing, that is our intermediate state is the same of the outgoing one. Moreover, at leading order, for completeness one should consider the interaction between particles in all possible way as shown in Fig. 2. The $S$-matrix (with the initial state = final state) can be written in the following way [27]

$$S = 1 + \frac{\pi}{p - \pi, \rho} \frac{p}{\bar{p} - \bar{\pi}, \rho} + 2 \frac{\pi}{p - \rho, \Delta} \frac{p}{\bar{p} - \bar{\rho}, \Delta},$$

FIG. 3: Diagrams that contribute to the rescattering. $\mathcal{P}$ is the Pomeron and $\pi, \rho, \Delta$ are Regge trajectories.

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$$S = 1 + 2i\sqrt{\lambda(s, m^2_P, m^2_P)} \frac{T^{P\bar{P}}(s)}{s} + 2i\sqrt{\lambda(x, m^2_P, m^2_P)} \frac{T^{P\pi}(x)}{x} + 2i\sqrt{\lambda(y, m^2_P, m^2_P)} \frac{T^{P\pi}(y)}{y},$$

(4)

where $\lambda(s, m^2_P, m^2_P)$ is the Kallén function and the $T$-matrices contains the elastic and also inelastic rescattering effects. From symmetry considerations we have $T^{P\pi} = T^{P\pi}$. The contributions to the $T$-matrices are shown in Fig. 3.

The leading contribution to the $T$-matrices, the Pomeron, can be parameterized, for small and negative transferred momentum $t$, in a universal form as [28]

$$\mathcal{P}(s, t) = -\beta(t) \left( \frac{s}{s_0} \right)^{\alpha_P(t)} e^{-i\frac{2}{3}\alpha_P(t)},$$

(5)

with $s_0 \approx O(1 \text{ GeV}^2)$ and $\alpha_P(t) = 1.08 + 0.25t$; this form is suggested by fit to hadron-hadron scattering total cross sections. The prefactor $\beta(t)$ in Equation (5) represents the Pomeron residue, that is Pomeron 'coupling' to the hadrons; phenomenologically it is given by [25, 29]

$$\beta(t) = \beta_P \frac{1}{(1-t/0.71)^2} \approx \beta_P e^{2.82t}.$$  

(6)

The coefficient $\beta_P$ writes in term of $\beta_{uu}^P$, the $\mathcal{P}$–quark coupling (we consider $SU(2)$ symmetry), and applying the additive quark counting rule [28] at each vertex; for instance for the first and the second diagram in Fig. 3 we have respectively:

$$\beta_{pp}^P = (3 \beta_{uu}^P)^2, \quad \beta_{p\pi}^P = (3 \beta_{uu}^P) (2 \beta_{uu}^P),$$

(7)

where $\beta_{uu}^P = 1.87 \text{ GeV}^{-1}$ [29].

The non-leading contributions to the rescattering are given by Regge trajectories. These amplitudes can be parameterized by means the Veneziano formula [30, 31] in the following way

$$\mathcal{R}(s, t) = -\beta_\mathcal{R} \frac{1 + (-1)^s \cos(\pi \alpha_R(t))}{2} \Gamma(\ell_\mathcal{R} - \alpha_\mathcal{R}(t)) (\alpha')^{1-\ell_\mathcal{R}} (\alpha' s)^{\alpha_\mathcal{R}(t)},$$

(8)

where $\Gamma$ is the Euler function and

$$\alpha_\mathcal{R}(t) = s_\mathcal{R} + \alpha'(t - m^2_{\mathcal{R}}),$$

(9)

is the Regge trajectory with the universal slope $\alpha' = 0.93 \text{ GeV}^{-2}$. In Table I we list the parameters $s_\mathcal{R}$, $\ell_\mathcal{R}$ and $m_\mathcal{R}$ for the trajectories $\pi$, $\rho$ and $\Delta$. $\beta_\mathcal{R}$ in Eq.(8) is the residue for the Regge trajectory and, as in the case of Pomeron, it factorizes in a product of two residue one for each diagram vertex. To estimate the Regge residue we note that near $t \approx m^2_\mathcal{R}$, Eq.(8) reduces to a Feynman-like amplitude [33]

$$\mathcal{R}(s, t) \approx -\beta_\mathcal{R} \frac{s^{s_\mathcal{R}}}{t - m^2_\mathcal{R}},$$

(10)
TABLE I: Parameters of the Regge trajectories.

| Trajectory | s_R | \ell_R | m_R(MeV) [32] |
|------------|-----|--------|--------------|
| \pi        | 0   | 0      | 139          |
| \rho       | 1   | 1      | 775          |
| \Delta     | 3/2 | 3/2    | 1232         |

which allows us to identify \( \beta^R \) as a product of coupling constants, one for each vertex.

To estimate the \( \Delta \)-proton–pion coupling we used an effective lagrangian approach with the experimental value of \( \Delta \to p\pi \) decay width. The interaction lagrangian can be written as

\[
\mathcal{L}_{\Delta p\pi} = g_{\Delta p\pi} \bar{\psi} \chi_\mu \partial^\mu \pi + \text{c.c.},
\]

where \( \psi \) is the standard fermionic field for the proton, \( \pi \) the pion field and \( \chi_\mu \) the Rarita-Schwinger tensor [34] for a \( \frac{3}{2} \)-spin field that describes the \( \Delta \). From Lagrangian in Eq.(11) one can calculate the following decay width

\[
\Gamma(\Delta \to p\pi) = \frac{1}{8\pi p_f^3} g_{\Delta p\pi}^2 (m_\Delta + m_p)^2 - m_\pi^2 \frac{3 m_\Delta^3}{4 m_\Delta^2},
\]

and by means his experimental value, \( \Gamma_{\text{exp}}(\Delta \to p\pi) = 118 \text{ MeV} \) at \( p_f = 229 \text{ MeV} \) [32], one can determinate the coupling constant

\[
g_{\Delta p\pi} = 15.4 \text{ GeV}^{-1}.
\]

In the following we will neglect the \( t \)-dependence of \( \beta^R_{\Delta p\pi} \) Regge residue and we will identify it as \( g_{\Delta p\pi} \). The other residues useful in our treatment are given by [31]

\[
\beta_{pp}^\pi = 25.2, \quad \beta_{p\pi}^\rho = 13.0, \quad \beta_{\pi\pi}^\rho = -8.0.
\]

Therefore the \( T \)-matrices present in Eq.(4) write as [29, 35]

\[
T^{p\bar{p}}(s) = \frac{1}{16\pi} \frac{s}{\lambda(s, m^2_p, m^2_{\bar{p}})} \int_{s+4m^2_p}^{0} P^{pp}(s, t) + R_{pp}^\pi(s, t) + R_{p\bar{p}}^\rho(s, t) \, dt
\]
\[
T^{p\pi}(x) = \frac{1}{16\pi} \frac{x}{\lambda(x, m^2_p, m^2_\pi)} \int_{m^2_p-x^2}^{0} P^{p\pi}(x, t) + R_{p\pi}^\rho(x, t) + R_{\pi\pi}^\Delta(x, t) \, dt,
\]

and finally the double differential width for \( B \to \pi p\bar{p} \), with the final state interaction effect take into account, is thus given by [35]

\[
d\Gamma' = \frac{1}{(2\pi)^3} \frac{1}{32m^2_B} |A|^2 \, dx \, ds = \frac{1}{(2\pi)^3} \frac{1}{32m^2_B} |\tilde{S}| |\tilde{A}|^2 \, dx \, ds.
\]

III. DISCUSSION AND RESULTS

The double differential width writes in Eq.(17) depends on two functions: (i) The bare amplitude \( \tilde{A} \) that describes the \( B \) decay vertex and (ii) the \( S \)-matrix \( S \) that describes the re-interaction between the outgoing particles. In Section II we discussed the rescattering contributions; the problem now is to understand the role that plays the bare amplitude in the full dynamics. How we saw in the Introduction experimental data show that the characteristic peak at the threshold in the proton-antiproton system as well as in other different baryonic systems has a very universal behaviour. On the other hand the bare amplitude should be strongly dependent from the dynamics of weak decay vertex, or in other words, it should be different for different final states. While the strong interactions are independent from dynamics of particle productions and they are very similar behaviour between hadrons. Therefore, how previously argued in the Introduction, one should realize that the dynamics of the process is principally dominated by rescattering interactions between baryons and \( B \) decay vertex plays a ‘fine-tuning’ role on the shape of differential width.
FIG. 4: Differential width of $B \to p\bar{p}\pi$ as function of invariant mass of proton-antiproton. Shared yellow region is just the phase-space $\Phi(s)$. Blue line refers to the final state interactions effect with only re-interaction in the proton-antiproton system ($T_{pp}$), while red line take into account full rescattering ($T_{pp} + 2T_{p\pi}$). Units are arbitrary.

FIG. 5: Dalitz plot of $B \to p\bar{p}\pi$ with re-interaction effects. We can distinguish two regions in the diagram: First on the left due to the Pomeron exchanged in proton-antiproton system and one at bottom on the right that is the exchange of the $\Delta$ between pion and (anti)proton.

In summary we neglect the variations of bare amplitude respect to $S$-matrix and we trait $\tilde{A}$ as was a constant. Thus if we turn-off the rescattering effects ($S = 1$) and we integrate-out the $x$ variable in Eq.(17), one obtains a differential width proportional to three-body phase-space $\Phi(s)$, namely

$$\Phi(s) = \frac{1}{2\pi^3 m_B^2 s} \sqrt{s - m_p^2} \sqrt{s - 4m_p^2},$$

that the bare amplitude can only modulate.

The effects of final state interactions on the differential width of $B \to p\bar{p}\pi$ (modulo $|\tilde{A}|^2$) are reported in Fig. 4 where the blue line takes into account only the effects of re-interaction between proton-antiproton (see Eq.(15)) while red curve contains the rescattering with the pion too (Eqq.(15) and (16)). There are two characteristics that emerge from full rescattering in Fig. 4: (i) The strong peak near to the threshold area and (ii) the ‘see-saw’ trend for higher values of $s$. Both are present in experimental data, compare for instance Fig. 1. These features are better understood if we look at the Dalitz plot in Fig. 5: how one can see from the structure of the Dalitz distribution, respect to the $s$ variable, the peak is essentially due to the Pomeron for rescattering between the baryonic pair (structure on the left of plot) while the latter is due to the presence of the Pomeron and $\Delta$ in the system pion-(anti)proton (structure on the bottom).

To further test our analysis we applied rescattering approach to the channels $B \to p\bar{p}K$, $B \to p\bar{p}K^*$ and $B \to p\bar{p}D$. In these cases for the systems $pK$, $pK^*$ and $pD$ we take into account only the Pomeron contribution; results are in Fig. 6. How one can see also in these cases the rescattering model is able to reproduce the peak near to the threshold area but in some cases, as in the channel $B \to p\bar{p}K^*$ for instance, the spectrum is not well reproduced for higher $s$: Probably in this case one should add another rescattering contributions between $K^*$ and (anti)proton, but the peak is, in any case, due to the rescattering between baryonic pair. Moreover the shape of spectrum is similar in the three
cases, but as the phase-space of $s$ variable become smaller (i.e. the outgoing mass of meson increase) the peak width tend to enlarge.

There is another support to our thesis of the re-interaction, and it comes again from experimental data. In fact recently BELLE studied $B$ decay channels with an heavy particle in the final state, precisely $B \to J/\psi \Lambda \bar{p}$ and $B \to J/\psi \bar{p}p$ [36]. From these measurements emerged that there is not threshold enhancement effect at all in the invariant mass of $\Lambda \bar{p}$ when there is a heavy meson in the final state (on the contrary the peak return if meson is light one as in the case $B \to J/\psi \pi$). Our results for $B \to J/\psi \Lambda \bar{p}$ and $B \to J/\psi \bar{p}p$ are reported in Fig. 7: For these cases we consider only the rescattering between baryon-antibaryon system because the phase-space of $x$ variable is small and it gives a negligible contribution to the full amplitude; moreover in the system antiproton-A we consider the contribution of Pomeron and the Regge trajectory of $\rho$. These two channels are the limit cases of $B \to \bar{p}pD$ where the phase-space of $s$ is so small that only the peak is present.

IV. CONCLUSIONS

In this paper we presented a simple model to understand the threshold enhancement effect present in the spectrum of many baryonic three-body $B$ (and $J/\psi$) decays. This model is based on hypothesis of re-interactions between outgoing particle. We studied in detail the $B \to \bar{p}p\pi$ channel because in this case we are able to make a full analysis of main rescattering diagrams in the proton-antiproton system as well as in the pion-(anti)proton system, but the results can be easily extend to other decay channels. Our principal ansatz is the constance of bare amplitude, or better, its variations from a channel decay to another are negligible respect to the rescattering effects. This feature is suggest from experimental behaviour.

In this framework we are able to reproduce the experimental enhancement effect near to the threshold area for $B \to \bar{p}p\pi$ decay (see Fig. 4) and with some change also in other decays where the pion is substituted by a heavier meson (see Fig. 6). We studied also two channels with a heavy meson in the final state, precisely $B \to J/\psi \bar{p}p$ and $B \to J/\psi \Lambda \bar{p}$ (see Fig. 7): in these cases due to the phase-space configuration the peak disappear, or better it span all spectrum. This feature has been experimentally observed in $B \to J/\psi \Lambda \bar{p}$ decay; on the other hand, for $B \to J/\psi \bar{p}p$
it is a theoretical prediction.

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