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Charge asymmetry in decays $B \to D\bar{D}K$

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Abstract: We discusses the charge asymmetry in $B \to D\bar{D}K$ decays with an invariant mass of the $D\bar{D}$ pair near the $\Psi(3770)$ resonance. Unlike $\Psi(3770)$ decays in e^+e^- annihilation, in B^+ decays the probability of $D^0\bar{D}^0$ production is almost three times higher than D^+D^-. In B^0 decays, the ratio of these probabilities will be opposite. The effect is explained by the fact that, in B -meson decays, the $D\bar{D}$ pair is produced in a superposition of isoscalar and isovector states, and only in combination with K -mesons the total state has 1/2 isospin. We present a simple model in which the interference of the nonresonant isovector amplitude with the resonant isoscalar amplitude explains the experimental data.

Keywords: B physics, e+-e- Experiments, Quarkonium

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Contents

1 Introduction

Recently, at LHC seminar at CERN [1, 2], the LHCb collaboration presented preliminary results of amplitude analysis of the decay $B \to D^+D^-K^+$. General attention was drawn to the presence of a peak at an energy 2.9 GeV in the distribution over the invariant mass of D^-K^+, figure 1. In the short time since the presentation, many articles have appeared offering different interpretations of this phenomenon [3–13].

These interpretations are based on the hypotheses on the production of a compact $\bar{c}\bar{s}ud$ tetraquark, D^*K^* molecules, etc. However, no one paid attention to another interesting phenomenon that is clearly manifested in the LHCb data. In the distribution over the invariant mass D^+D^- (figure 2) in the decay $B^+ \to D^+D^-K^+$, two peaks are observed, which are interpreted by the authors [1], as signals of charmonia $\Psi(3770)$, $\chi_{c0}(3930)$, and $\chi_{c2}(3930)$. It would seem that such an interpretation is natural. However, if we look at the invariant mass distribution of $D^0\bar{D}^0$ in the decay $B^+ \to D^0\bar{D}^0K^+$ [14], figure 3, then we will see only peak $\Psi(3770)$.

At first glance, we observe a contradiction, since the isotopic spin of charmonia is zero, and, therefore, the probabilities of their decays into D^+D^- and $D^0\bar{D}^0$ should be equal. This is precisely what is observed in the decays of $\Psi(3770)$ produced in e^+e^- annihilation. Our work is devoted to the possible interpretation of the apparent contradiction.

2 Charge asymmetry in $B \to D\bar{D}K$ decays

Assume that the masses of charged and neutral D-mesons coincide, i.e., the violation of isotopic invariance associated with the difference of u and d quark masses is absent. Consider the production of $D\bar{D}$ pairs in B^+ decays with an invariant mass near $M =$ 3770 MeV and estimate in this region the ratio of the decay probabilities

$$R = W(B^+ \to D^+D^-K^+)/W(B^+ \to \bar{D}^0D^0K^+).$$

Since the LHCb [1] does not present the absolute decay probability W^{+-}_{tot} of the decay $B^+ \to D^+D^-K^+$, but only the fraction $W^{+-}_{\text{Res}}/W^{+-}_{\text{tot}}$ of this decay probabilities in the vicinity of $\Psi(3770)$ resonance, see table 1, then we use the results of Babar [15], $W^{+-}_{\text{tot}} =$ $(2.2 \pm 0.5 \pm 0.5) \cdot 10^{-4}$, the result of LHCb (table 1), and obtain $W^{+-}_{\text{Res}} = (3.2 \pm 0.77 \pm 0.75) \cdot$

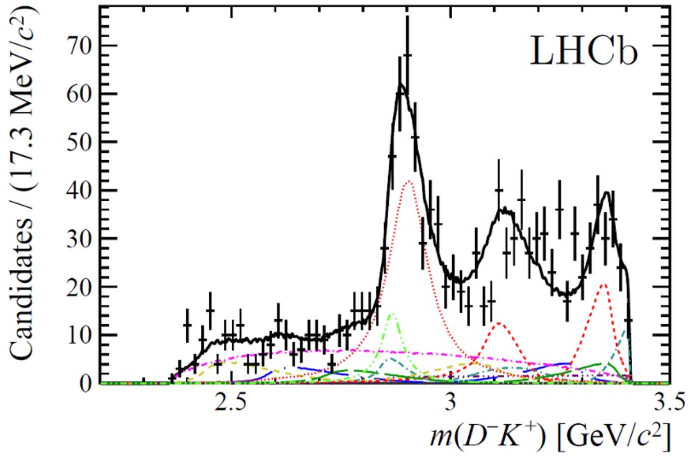

Figure 1. Distribution over the invariant mass of D^-K^+ in the decay $B^+ \to D^+D^-K^+$ in the LHCb [1] data. The dots show the data, the curves show the resulting fit function and the contributions of the individual components of the model.

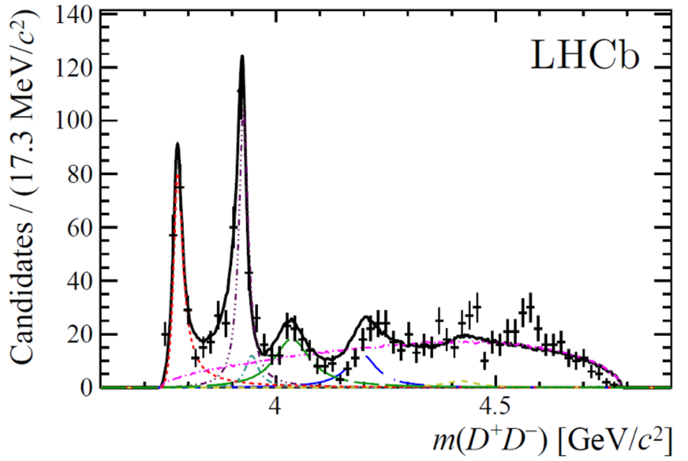

Figure 2. The distribution over the invariant mass of D^-D^+ in the decay $B^+ \to D^+D^-K^+$ in the LHCb [1] data. The dots show the data, the curves show the resulting fit function and the contributions of the individual components of the model.

10^{-5}. Comparing this value with the corresponding value $W^{00}_{\text{Res}} = (11.8 \pm 4.1 \pm 1.5) \cdot 10^{-5}$, for the decay $B^+ \to D^0\bar{D}^0K^+$ [14], we find the ratio $R = 0.27 \pm 0.13$ (the statistical and systematic errors were added quadratically to the total uncertainty), which is three times less than the ratio obtained in e^+e^- annihilation by CLEO [16], $0.799 \pm 0.006 \pm 0.008$, and by BESIII [17], $0.7823 \pm 0.0036 \pm 0.0093$.

The R ratio can also be obtained from the Belle [19] and Babar [18] data. Note that both measurements did not use amplitude analysis to obtain the number of events. Belle [19] obtained the ratio $R = 0.41 \pm 0.25 \pm 0.073$. Babar [18] does not present the corresponding value, although it follows from the data of [18] that $R = 0.6 \pm 0.31$. It is seen that the experimental accuracy of B-factories is insufficient for any unambiguous conclusions.

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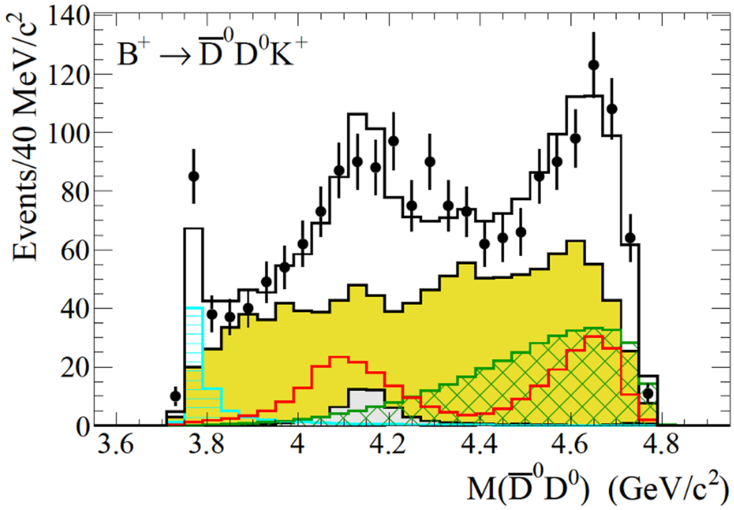

Figure 3. The distribution over the invariant mass of $D^0\bar{D}^0$ in the decay $B^+ \to D^0\bar{D}^0K^+$ in the Babar [14] data. The dots show the data, the histograms show the resulting description by the model and individual contributions.

Resonance	Magnitude	Phase (rad)	Fit fraction (%)
D^+D^- resonances			
$\psi(3770)$	1 (fixed)	0 (fixed)	$14.5 \pm 1.2 \pm 0.8$
$\chi_{c0}(3930)$	$0.51 \pm 0.06 \pm 0.02$	$2.16 \pm 0.18 \pm 0.03$	$3.7 \pm 0.9 \pm 0.2$
$\chi_{c2}(3930)$	$0.70 \pm 0.06 \pm 0.01$	$0.83 \pm 0.17 \pm 0.13$	$7.2 \pm 1.2 \pm 0.3$
$\psi(4040)$	$0.59 \pm 0.08 \pm 0.04$	$1.42 \pm 0.18 \pm 0.08$	$5.0 \pm 1.3 \pm 0.4$
$\psi(4160)$	$0.67 \pm 0.08 \pm 0.05$	$0.90 \pm 0.23 \pm 0.09$	$6.6 \pm 1.5 \pm 1.2$
$\psi(4415)$	$0.80 \pm 0.08 \pm 0.06$	$-1.46 \pm 0.20 \pm 0.09$	$9.2 \pm 1.4 \pm 1.5$
D^-K^+ resonances			
$X_0(2900)$	$0.62 \pm 0.08 \pm 0.03$	$1.09 \pm 0.19 \pm 0.10$	$5.6 \pm 1.4 \pm 0.5$
$X_1(2900)$	$1.45 \pm 0.09 \pm 0.03$	$0.37 \pm 0.10 \pm 0.05$	$30.6 \pm 2.4 \pm 2.1$
Nonresonant	$1.29 \pm 0.09 \pm 0.04$	$-2.41 \pm 0.12 \pm 0.51$	$24.2 \pm 2.2 \pm 0.5$

Table 1. Fitfractions, amplitudes and phases of two-particle intermediate states in the amplitude analysis of the $B^+ \to D^+D^-K^+$ decay in the LHCb [1] data.

The ratio R derived from LHCb data is more accurate than previously published values and is consistent with them within errors. Thus, we see that the signal $D^0\bar{D}^0$ in the resonance region is many times greater than that of D^+D^-. Perhaps this effect explains the apparent difference in the probability of $D^0\bar{D}^0$ production in the region of invariant masses of $\Psi(3770)$ and χ_{c0}/χ_{c2}. In addition, we come to the important conclusion that the hadronic system of $D\bar{D}$ produced in B^+ decay in the vicinity of $\Psi(3770)$ differs from the resonance $\Psi(3770)$ observed in e^+e^- annihilation. How can this large charge asymmetry be explained?

In terms of quarks, the decay $B^+ \to D\bar{D}K$ corresponds to the process

$$u\,\bar{b} \to u\,(c\,\bar{c}\,\bar{s})(u\,\bar{u} + d\,\bar{d}),$$

where we took into account a light quark-antiquark pair with zero isospin $(u\,\bar{u} + d\,\bar{d})$ produced from the vacuum. There are two options: the spectator u goes into a bound state with the antiquark $\bar{s}$ or with $\bar{c}$. As a result, the wave function ψ of the final state can be written as

$$\psi = a\,\frac{(D^0\,\bar{D}^0 - D^+\,D^-)}{\sqrt{2}}\,K^+ + b\,\frac{(D^0\,K^+ - D^+\,K^0)}{\sqrt{2}}\,\bar{D}^0\,.$$

Here the states in parentheses have an isospin equal to zero; we consider only the quark composition and not discuss spin, angular momentum or other quantum numbers. The wave function ψ must be rewritten in terms of quasiparticles, which are systems of strongly interacting $D\bar{D}$. From the isospin point of view, there are two such systems: states with isospin zero and one. We have

$$\begin{aligned}
\psi &= (a + b/2)\psi_0 + \frac{\sqrt{3}}{2}\,b\,\psi_1\,,\\
\psi_0 &= |0,0\rangle\,|1/2,1/2\rangle\\
&= \frac{(D^0\,\bar{D}^0 - D^+\,D^-)}{\sqrt{2}}\,K^+\\
\psi_1 &= \frac{1}{\sqrt{3}}|1,0\rangle\,|1/2,1/2\rangle - \sqrt{\frac{2}{3}}|1,1\rangle\,|1/2,-1/2\rangle\\
&= \frac{1}{\sqrt{3}}\,\frac{(D^0\,\bar{D}^0\; + D^+\,\bar{D}^-)}{\sqrt{2}}\,K^+ - \sqrt{\frac{2}{3}}D^+\,\bar{D}^0\,K^0\,.
\end{aligned} \tag{2.1}$$

Thus, ψ_0 is a system consisting of interacting $D\bar{D}$ with isospin zero and K^+, ψ_1 is a system consisting of interacting $D\bar{D}$ with isospin one and K^+ or K^0 with total isospin $1/2$ and projection $+1/2$. The problem under discussion is similar to the well-known problem of the production of nucleon-antinucleon pairs in e^+e^- annihilation near the threshold, since in this case the hadronic state is a superposition of the isovector and isoscalar parts. The non-trivial dependence of the cross section on the energy near the pair production threshold is explained by the interaction of slow nucleons and antinucleons through a strong optical potential [20–22]. Optical potentials are different for the isovector and isoscalar states. The imaginary part of the optical potential takes into account the processes of annihilation of a nucleon-antinucleon pair into mesons.

Since our goal is not to obtain accurate predictions, which is a very non-trivial task, but to explain the phenomenon at the qualitative level, we consider the simplest model, which, nevertheless, contains all essential features of a real problem.

Consider the simplest case $M_c = M_0 = M$, where M_c and M_0 are masses, respectively, of charged and neutral D-mesons. The optical interaction potential is denoted by $U_0(r)$ for the isosinglet state and by $U_1(r)$ for the isotriplet state. For simplicity, we assume that the $D\bar{D}$ pair is in a state with an orbital angular momentum $l = 0$ (as will be explained below, the asymmetry mechanism for the case $l = 1$ does not qualitatively differ from the case $l = 0$). To find the decay probability, we use the approach described in the works [20–22]. First, it is necessary to find regular solutions $u_n(r)$ of the equations

$$\left[\frac{p_r^2}{M} + U_n(r) - E\right] u_n(r) = 0\,, \quad n = 0,\, 1\,,$$

where $(-p_r^2)$ is the radial part of the Laplace operator. For $r \to \infty$, the asymptotic form of the solutions is

$$\begin{aligned} u_n(r) &= \frac{1}{2i}[S_n\,\chi_k^+ - \chi_k^-]\,, & |S_n| &\le 1\,, \\ \chi_k^+ &= \frac{\exp(ikr)}{kr}\,, & \chi_k^- &= \frac{\exp(-ikr)}{kr}\,, \qquad k = \sqrt{ME}\,. \end{aligned} \tag{2.2}$$

After that, the probabilities W^{+-}, W^{00}, and W^{+0} of decays, respectively, $B^+ \to D^+D^-K^+$, $B^+ \to D^0\bar{D}^0K^+$ and $B^+ \to D^+\bar{D}^0K^0$ can be expressed up to a common factor in terms of $u_n(0)$ as follows

$$\begin{aligned} W^{+-} &= \left| -\left(a + \frac{b}{2}\right) u_0(0) + \frac{b}{2}\, u_1(0) \right|^2\,, \\ W^{00} &= \left| \left(a + \frac{b}{2}\right) u_0(0) + \frac{b}{2}\, u_1(0) \right|^2\,, \\ W^{+0} &= |b\, u_1(0)|^2\,. \end{aligned} \tag{2.3}$$

The charge asymmetry is determined not only by the values of a and b, which can be considered energy independent near the threshold of $D\bar{D}$ pair production, but also by the values of the functions $u_0(0)$ and $u_1(0)$ having the energy dependence determined by the isoscalar and isovector optical potentials, respectively. To explain the charge asymmetry, it is convenient to introduce the variable

$$x = \left(\frac{2a}{b} + 1\right) \frac{u_0(0)}{u_1(0)} \tag{2.4}$$

and rewrite the expressions for the probabilities as

$$W^{+-} = \frac{1}{4} F\, |x - 1|^2\,, \quad W^{00} = \frac{1}{4} F\, |x + 1|^2\,, \quad W^{+0} = F\,, \tag{2.5}$$

where F is some function of energy that does not affect the probability ratio. All information about the charge asymmetry is contained in the variable x, which is, generally speaking, a complex quantity.

Similar expressions can be obtained for the decay probabilities of a neutral B-meson, $B^0 \to \bar{D}DK$. In this decay the wave function $\widetilde{\psi}$ of the final state is

$$\begin{aligned} \widetilde{\psi} &= (a + b/2)\widetilde{\psi}_0 - \frac{\sqrt{3}}{2}\, b\, \widetilde{\psi}_1\,, \\ \widetilde{\psi}_0 &= \frac{(D^0\,\bar{D}^0 - D^+\,D^-)}{\sqrt{2}}\, K^0 \\ \widetilde{\psi}_1 &= \frac{1}{\sqrt{3}}\, \frac{(D^0\,\bar{D}^0 + D^+\,\bar{D}^-)}{\sqrt{2}}\, K^0 - \sqrt{\frac{2}{3}} D^0\, D^-\, K^+\,. \end{aligned} \tag{2.6}$$

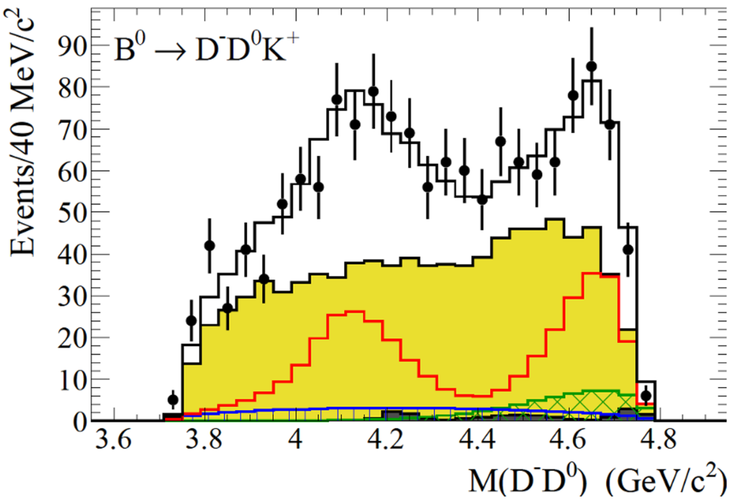

Figure 4. The invariant mass distribution of D^0D^- in the decay $B^0 \to D^0D^-K^+$ in the Babar [14] data. The dots show the data, the histograms show the resulting description by the model and individual contributions.

Therefore, for the probabilities $\tilde{W}^{+-}$, $\tilde{W}^{00}$ and $\tilde{W}^{0-}$ in B^0 decay into $D^+D^-K^0$, $D^0\bar{D}^0K^0$, and $D^0D^-K^+$, respectively, we obtain:

$$\widetilde{W}^{+-} = W^{00}\,, \quad \widetilde{W}^{00} = W^{+-}\,, \quad \widetilde{W}^{0-} = W^{+0}\,. \tag{2.7}$$

Since it follows from the experiment that peaks in the invariant mass of D^0D^- in the energy region of $\Psi(3770)$ resonance are not observed in the decay $B^0 \to D^0D^-K^+$, see figure 4, then it is natural to consider the function $u_1(0)$ to be independent of energy. The energy dependence of the function $u_0(0)$ has a resonant form and can be found from the cross section of $\Psi(3770)$ production in e^+e^- annihilation, in which $D\bar{D}$ is in the isoscalar state. As a result, the dependence of the function x on energy has the form:

$$x = \frac{C}{E - E_0 + i\Gamma/2}\,, \tag{2.8}$$

where $E_0 = \Gamma = 30\,\text{MeV}$, and C is some complex parameter.

Figure 5 shows the energy dependence of the probabilities W^{00} and W^{+-} in units of W^{+0} for $|C| = 45\,\text{MeV}$, which reproduces the experimentally observed charge asymmetry for some $\arg C$. These dependencies are very sensitive to the phase value of the parameter C. For $\arg C = \pi/2$, good agreement with experiment is seen. The value of charge asymmetry R for the selected parameters is 0.25. For $\arg C = 0$, the charge asymmetry disappears. It is important that the interference between the resonant isoscalar and non-resonant isovector amplitudes can lead not only to charge asymmetry, but also to distortion of the resonance shape and its parameters in different decay channels.

We emphasize that the picture of charge asymmetry described above for the case of the $\bar{D}D$ system with orbital angular momentum $l = 0$ is completely preserved for $l = 1$. The only modification is an explicit expression for the function x (2.4), where the ratio of derivatives $u_0'(0)/u_1'(0)$ should be used instead of the ratio $u_0(0)/u_1(0)$. However, the resonant form of the function x (2.8) is preserved.

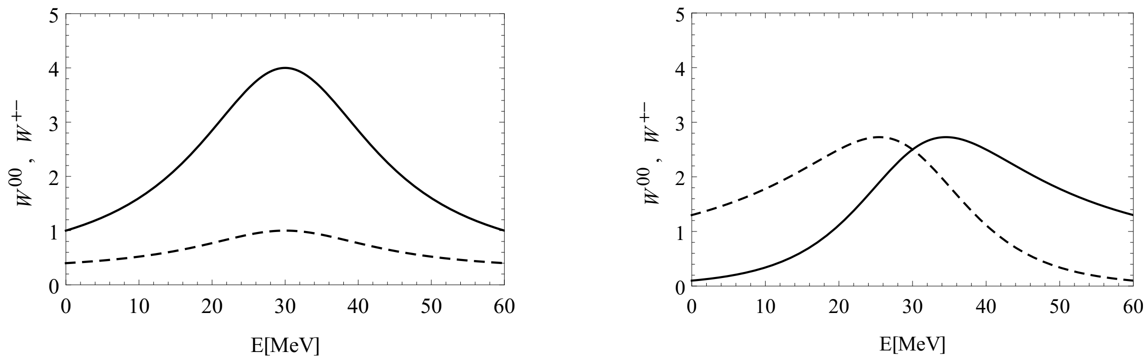

Figure 5. Energy dependence of the probabilities W^{00} (solid line) and W^{+-} (dashed line) in units of W^{+0} for $|C| = 45\,\mathrm{MeV}$, $\arg C = \pi/2$ (left figure) and $\arg C = 0$ (right figure).

3 Conclusion

In our work, we indicated a large difference in the probabilities of $B^+ \to D^+D^-K^+$ and $B^+ \to D^0\bar{D}^0K^+$ decays for the invariant mass of $D\bar{D}$ pair in the vicinity of the resonance $\Psi(3770)$. This difference follows from the experimental data of LHCb and Babar. The ratio of the probabilities is $R = 0.27 \pm 0.13$. It is shown that such a large charge asymmetry is apparently related to the interference between the resonant isoscalar and nonresonant isovector amplitudes of $D\bar{D}$ pair production. The simple model we constructed is in good agreement with the experimental data. We predict that, up to the effects associated with a small difference in the masses of charged and neutral D-mesons, the value of R will be inverse in the decay of B^0 meson. Similar effects should be expected in other decays of B -mesons, such as $B \to D^{(*)}\bar{D}^{(*)}K$, for invariant masses of $D^{(*)}\bar{D}^{(*)}$ near the corresponding resonances. We have shown that the interference between the resonant isoscalar and nonresonant isovector amplitudes can lead not only to charge asymmetry, but also to a significant distortion of the resonance shape and its parameters in different decay channels. Therefore, it is important to take into account the contribution of the isovector amplitude in the amplitude analysis of B-meson decays. The relations (2.3) allow us to formulate a recipe for the correct extraction of the $D\bar{D}$ isoscalar resonance contribution to the decay probability $B \to D\bar{D}K$. This contribution is determined by the combination $W^{+-} + W^{00} - W^{+0}/2$. Namely, the Dalitz plot corresponding to the isoscalar contribution to the decay probability of the B meson can be obtained by combining the densities of events corresponding to each channel, according to the combination pointed out above.

Acknowledgments

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