Abstract

Data on \( B^+ \rightarrow J/\psi \phi K^+ \) and the \( Y(4140) \) enhancement recently reported by the CDF Collaboration [1] are analyzed. The threshold behavior, as well as traces of the \( X(4260) \) enhancement, the known \( c \bar{c} \) resonances \( \psi(2D), \psi(4S) \), and a tentative \( \psi(3D) \) state, as observed in the mass distribution, suggest that the \( J/\psi \phi \) system has quantum numbers \( J^P C = 1^- \). It is then argued that the \( Y(4140) \) enhancement does not represent any kind of resonance, but instead is a natural consequence of the opening of the \( J/\psi \phi \) channel.

In Ref. [1], the CDF Collaboration displayed the invariant-mass spectrum of \( J/\psi \phi \) for the world’s largest sample (75 events) of exclusive \( B^+ \rightarrow J/\psi \phi K^+ \) decays, produced in \( \bar{p}p \) collisions at \( \sqrt{s} = 1.96 \) TeV, and collected by the CDF-II detector at the Tevatron (Fermilab). The experimental analysis revealed evidence for a narrow structure near the \( J/\psi \phi \) threshold, with significance in excess of 3.8\( \sigma \). Assuming an S-wave relativistic Breit-Wigner approximation, the mass and width of this structure were determined as \( 4143.0 \pm 2.9 \) (stat) \( \pm 1.2 \) (syst) MeV/c, and \( 11.7^{+8.3}_{-5.0} \) (stat) \( \pm 3.7 \) (syst) MeV/c, respectively.

The \( J/\psi \phi \) enhancement, which was baptized \( Y(4140) \) by the CDF Collaboration, has been studied in a variety of theoretical models, namely as a \( D^*_s \bar{D}^*_s \) molecule with \( J^{PC} = 0^{++} \) or \( J^{PC} = 2^{++} \), [2–6] or an exotic hybrid charmonium state with \( J^{PC} = 1^{-+} \) [3,7]. It was also shown that the \( Y(4140) \) is probably not the second radial excitation of any of the \( P \)-wave charmonium states [8]. Finally, in Ref. [7] it was argued that the \( Y(4140) \) cannot be a \( D^*_s \bar{D}^*_s \) molecule. Surprisingly, no tetraquark proposals have circulated yet.

The CDF Collaboration observed that the \( J/\psi \phi \) enhancement is well above the threshold for open-charm decays, and a \( c \bar{c} \) charmonium resonance with this mass would be expected to
decay dominantly into an open-charm pair, with only a tiny branching fraction into $J/\psi \phi$ [9, 10]. Consequently, according to the CDF Collaboration, this structure is not compatible with conventional expectations for a charmonium resonance.

Indeed, the $Y(4140)$ enhancement lies relatively close to open-charm thresholds, namely $D_sD_s^*$, $D^*D^*$, $D_sD_s$, and $DD^*$, at 4.076, 4.02, 3.939, and 3.875 GeV, respectively. However, branching fractions have been measured at 4.028 GeV, with the SLAC/LBL magnetic detector at SPEAR [11]. The results suggest that the opening of a channel is followed by a rather fast falling-off at higher invariant masses [12]. For conservative parameters, we find that at 4.14 GeV the $DD^*$ channel has almost completely faded out, whereas the other three open–charm channels, viz. $D_sD_s$, $D^*D^*$, and $D_sD_s^*$, are reduced to less than 2%, 10%, and 25%, respectively. Taking into account the combinatorial factors as well, we find that actually not so much open-charm decay should be expected at 4.14 GeV.

A related observation, for pion multiplicities in proton-antiproton annihilation [13, 14], shows that a $p\bar{p}$ system at rest does not preferably decay into pairs of pions, but instead into several more pions, with a maximum of five, probably through other resonances [15]. Apparently, excess of kinetic energy does not contribute to the conditions in which resonances can be formed. Here, we study the formation of a $J/\psi \phi$ pair of resonances, which we thus expect to be at maximum just above threshold. Similar phenomena have been observed for $J/\psi \rho$ [16], $J/\psi f_0(980)$ [17,18], $\psi(2S)f_0(980)$ [19], and $\Lambda_c\bar{\Lambda}_c$ [20].

In Fig. 1, we display the events recorded by the CDF Collaboration [1]. The signal shows a clear and narrow peak, which sets out at the $J/\psi \phi$ threshold. Some minor structures at about 4.27, 4.40, and 4.53 GeV are less significant.

The weak decay $B^+ \rightarrow Y(4140)K^+$ does not necessarily conserve parity, so the final $Y(4140)K^+$ state may have either $J^P = 0^-$ or $J^P = 0^+$. In the $J^P = 0^-$ scenario, since the $K^+$ is also a pseudoscalar, the simplest assignments for the $Y(4140)$ are a scalar in a relative $S$ wave with the $K^+$, or a vector in a $P$ wave. On the other hand, if $Y(4140)K^+$ has $J^P = 0^+$, then the $Y(4140)$ can be either a pseudoscalar in a relative $S$ wave with the $K^+$, or an axial vector in a $P$ wave. Also, the $Y(4140)$ decays into a pair of vector particles. For a scalar or axial vector, this can be either in an $S$ wave or a $D$ wave, whereas for a pseudoscalar or vector it can only be in a $P$ wave.

![Figure 1: Experimental invariant-mass distribution of $J/\psi \phi$ for $B^+$ decays into $J/\psi \phi K^+$, from the CDF Collaboration [1]. With arrows we indicate the central-mass positions of the well-established $\psi(2D, 4160)$ and $\psi(4S, 4415)$ $c\bar{c}$ resonances [21,22], as well as the recently discovered $\psi(3D, 4530-4550)$ [23,24] $c\bar{c}$ state. Moreover, the threshold energy [21] of the $D_s^*D_s^*$ channel is shown.](image-url)
wave. Moreover, from the data of the CDF Collaboration [1], and assuming a natural opening of the \( J/\psi \phi \) channel, as well as the absence of resonances in the \( J/\psi \phi \) system in the relevant energy interval, we conclude from the behavior of the signal near the \( J/\psi \phi \) threshold that the system is most probably in a relative \( P \) wave [25]. If indeed so, we are left with the assignments \( J^P = 0^- \) and \( J^P = 1^- \) for the \( Y(4140) \). Furthermore, there seem to be significant structures in the CDF [1] data, displayed in Fig. 1 near the \( \psi(4S, 4415) \) and tentative \( \psi(3D, 4530-4550) \) [23,24] vector resonances, thus suggesting \( J^P = 1^- \) for the \( J/\psi \phi \) system.

We are well aware that the CDF Collaboration assumed an \( S \) wave for the \( J/\psi \phi \) system in Ref. [1]. Nevertheless, based on our observations above, we are more inclined to choose vector quantum numbers as our working hypothesis. Moreover, there appears to be an enhancement at about 4.27 GeV in Fig. 1. This coincides with the invariant-mass region where, by studying the \( e^+e^- \rightarrow J/\psi \pi^+\pi^- \) cross section, the BABAR Collaboration discovered a new vector enhancement, originally baptized as \( Y(4260) \) [17], but now included in the PDG tables as \( X(4260) \) [21]. If the structure observed here indeed corresponds to the \( X(4260) \), then our vector assignment for the \( J/\psi \phi \) system is quite reasonable.

Next we shall discuss whether the \( Y(4140) \) enhancement should be interpreted as a new resonance. Resonances are characterized by complex poles in the scattering amplitude [26–28]. From Refs. [26,27] we learn that the \( c\bar{c} \) pole spectrum is very rich, and has in the mass region 4.0–4.2 GeV some 11 resonances, for \( J^{PC} = (0,2,4)^{--} \) and \( J^{PC} = (1,2,3,4,5)^{--} \), where, moreover, \( J^{PC} = (1,3,5)^{--} \) can have two different angular excitations. Furthermore, dynamically generated poles may show up as well [29], just like the dynamically generated nonet of light scalar mesons [28,30], and the variety of examples for open charm and beauty [31–33].

Unfortunately, most of the \( c\bar{c} \) resonances are still awaiting discovery in experiment. However, no matter if observed or not, we expect a very rich charmonium spectrum for higher invariant masses. Adding to that possible tetraquarks, molecules, and hybrids would saddle us up with an approximate continuum of resonances. However, do not support such a classification scheme of cross-section peaks showing up in experiment. We tend to believe that not every bump represents a new resonance, besides the fact that true resonances may have very different appearances in experiment, and even may manifest themselves through the absence of any signal [24,34]. In particular, if we take for the resonance position of the \( \psi(2D, 4160) \) the latest result of the BES Collaboration, namely \( 4191.7 \pm 6.5 \text{ MeV} \) [22], we see that the average mass of the \( Y(4140) \) structure lies well in between the peaks of the \( \psi(3S, 4040) \) and \( \psi(2D, 4160) \) resonances. As for open-charm decay, we expect its main influence near the central resonance masses, where the \( c\bar{c} \) system resonates most strongly. We shall come back to this point later on.

In Ref. [12], we discussed two distinct modes for the decay of a \( c\bar{c} \) system. One is through string breaking, giving rise to OZI-allowed pair creation, in which the \( c \) quark and \( \bar{c} \) antiquark recombine with the created quark and antiquark, resulting in charm-meson decay. The other mode corresponds to — OZI-forbidden — \( q\bar{q} \) emission, probably taking place in the gluon cloud surrounding the charmed constituents. In such processes, the \( c\bar{c} \) propagator radiates off systems of light quarks, and then jumps to its ground state [17] or to a lower-lying excitation [19]. It is well known that OZI-forbidden processes are suppressed with respect to OZI-allowed ones [35]. In Ref. [12], we tried to quantify the difference in probability for these two distinct processes. However, it is important to notice that coupling to virtual \( q\bar{q} \) pairs in the gluonic periphery may happen at any energy, so that no specific mass can be associated with it.

In the present case, we are considering the formation of pairs of \( J/\psi \) and \( \phi \) resonances. According to the prior discussion, this is most likely to happen just above threshold, via an \( s\bar{s} \) quark-antiquark pair created in the peripheral glue. Such an \( s\bar{s} \) pair couples to a dressed...
s\bar{s} propagator that contains all s\bar{s} resonances, viz. \( \eta, \eta', f_0(980), \phi \), and so forth [36]. By concentrating on \( K^+K^- \) in the experimental analysis [1], one will thus first observe the lowest possible resonance in this channel, which is the \( \phi \). There actually is little surprise in such a result. But its study is very important, and may certainly help in leading us to a theory for the formation of hadrons. Let us next focus on the results of the CDF Collaboration, displayed in Fig. 1.

The signal sets out from the \( J/\psi \phi \) threshold at 4116.37 \( \pm \) 0.03 GeV [21] upwards, and seems to rise linearly towards its maximum. This indicates a relative \( P \) wave, as we already stated in the foregoing, so \( S \) and \( D \) waves seem to be excluded. This implies that \( J = 0 \) or \( J = 2 \), assumed for molecular explanations [2–6], are not very plausible. However, the signal never reaches its true maximum, because of the presence of the \( \psi(2D, 4160) \) resonance. In Fig. 2 we have depicted the situation.

![Figure 2: Experimental invariant-mass distribution of \( J/\psi \phi \), for \( B^+ \) decays into \( J/\psi \phi K^+ \), from the CDF Collaboration [1]. The solid line (blue) stands for a simple Breit-Wigner approximation of the \( \psi(2D, 4160) \) [22] resonance.](image)

From Fig. 2 it is clear that some \( J/\psi \phi \) signal is missing exactly where one expects many charm-meson pairs to be formed, viz. around the peak of the \( \psi(2D, 4160) \) resonance. In Refs. [24, 34], we argued that the latter process takes place via string breaking, and is moreover faster than peripheral emission of \( s\bar{s} \) pairs. Consequently, open-charm decays deplete the \( c\bar{c} \) propagator well before it can decay into \( J/\psi \phi \). However, another important observation can be made here. Namely, there is quite some spreading [21] in the experimental results for the mass and width of the \( \psi(2D, 4160) \). Here, we have used the values of Ref. [22], which seem to agree well with the data of the CDF Collaboration. Hence, a precision experiment for the \( J/\psi \phi \) signal could be an adequate alternative method to establish the mass and width of this charmonium resonance.

For the feeble signal in the 4.26 GeV region, exactly the same arguments hold as for the \( X(4260) \), which we presented in Ref. [12]. Namely, near the threshold of the OZI-allowed \( D_s^*\bar{D}_s^* \) channel, the \( c\bar{c} \) propagator is in an \( s\bar{s} \)-rich environment. The latter also couples to the \( s\bar{s} \) propagator, probably most to the \( f_0(980) \) part, but certainly also to the \( \phi \). On the one hand, \( s\bar{s} \) creation in the inner region near the fast oscillating \( c\bar{c} \) pair, takes signal away from the peripheral process \( c\bar{c} \to J/\psi \phi \), via open-charm decay. But on the other hand, enhanced \( s\bar{s} \) creation in the inner region due to opening of the \( D_s^*\bar{D}_s^* \) channel gives rise to a higher probability of \( s\bar{s} \) pairs to escape from that region. For the \( X(4260) \) in \( J/\psi \pi\pi \), this leads to a positive net balance [12], and so probably also for \( J/\psi \phi \).
As far as the remaining part of the $J/\psi\phi$ mass distribution is concerned, we may observe from Fig. 1 that some effect of the negative interference of the $\psi(4S, 4415)$ is visible, albeit with little statics. Nevertheless, at the place where we predicted [23, 24] the $\psi(3D, 4530-4550)$ resonance, some signal is clearly visible, which seems to confirm our prediction.

In summary, we may conclude that the $J/\psi\phi$ system in exclusive $B^+ \to J/\psi\phi K^+$ decays probably has quantum numbers $J^{PC} = 1^{--}$, and that the bump at 4.14 GeV does not represent any resonance. The results of the CDF Collaboration are nonetheless a very valuable contribution to our understanding of strong interactions and hadron formation.

We have also indicated how and where previously observed structures, viz. the $X(4260)$, $\psi(2D)$, $\psi(4S)$, and the preliminary $\psi(3D)$, show up in the data of the CDF Collaboration.

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