Evidence for a Narrow Near-Threshold Structure in the $J/\psi\phi$ Mass Spectrum in $B^+ \to J/\psi\phi K^+$ Decays

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Evidence is reported for a narrow structure near the $J/\psi\phi$ threshold in exclusive $B^+ \to J/\psi\phi K^+$ decays produced in $\bar{p}p$ collisions at $\sqrt{s} = 1.96$ TeV. A signal of 14 ± 5 events, with statistical significance in excess of 3.8 standard deviations, is observed in a data sample corresponding to an integrated luminosity of 2.7 fb^{-1}, collected by the CDF II detector. The mass and natural width of the structure are measured to be $4143.0 \pm 2.9(\text{stat}) \pm 1.2(\text{syst})$ MeV$/c^2$ and $11.7^{+8.3}_{-5.0}(\text{stat}) \pm 3.7(\text{syst})$ MeV$/c^2$.

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Heavy quarkonium spectroscopy provides insight into strong interactions that are not precisely predictable by QCD theory. The recently discovered states that have charmoniumlike decay modes [1–4] but are difficult to place in the overall charmonium system have introduced new challenges. The possible interpretations beyond quark-antiquark states ($q\bar{q}$) such as hybrid ($q\bar{q}g$) and four-quark states ($q\bar{q}q\bar{q}$) have revitalized interest in exotic mesons in the charm sector [5–8]. An important tool in unraveling the nature of the states in the charmonium-mass region is the exploration of states in diverse channels. First, the $J/\psi\phi$ final state, with positive C parity, and two $J^{PC} = 1^{--}$ vector mesons (VV), is a good channel for an exotic meson search. The discovery of the $X(3872)$ (proposed as a four-quark state ($c\bar{c}q\bar{q}$) [7,8]) and $Y(3930)$ [2], both decaying into VV [9], suggests searching for other possible VV states [10]. Second, the observation of $Y(3930)$ near the $J/\psi\omega$ threshold motivates searches for similar phenomena near the $J/\psi\phi$ threshold. Third, the observation of the $Y(4260)$, a potential hybrid candidate [6], leads to an expectation of a triplet of hybrid states $J^{PC} = (0, 1, 2)^{-+}$ to lie nearby in mass [11,12], which would be accessible in the $J/\psi\phi$ channel. Finally, other possibilities such as glueballs [12] and nuclear-bound quarkonium [13] also motivate a search in this channel. The $J/\psi\phi$ channel is accessible in the decay mode $B^+ \to J/\psi\phi K^+$, which has been observed [14]. However, to date no results have been reported for substructure in the $J/\psi\phi$ channel.

In this Letter, we report an investigation of the $J/\psi\phi$ system produced in exclusive $B^+ \to J/\psi\phi K^+$ decays with $J/\psi \to \mu^+\mu^-$ and $\phi \to K^+K^-$. The search in exclusive B^+ decays is more sensitive than an inclusive search since the additional B^+ mass constraint on the $J/\psi\phi K^+$ system helps to reduce background. This analysis is based on a data sample of $\bar{p}p$ collisions at $\sqrt{s} = 1.96$ TeV with an integrated luminosity of 2.7 fb^{-1} collected by the CDF II detector at the Tevatron. Charge conjugate modes are included implicitly in this Letter.

The CDF II detector has been described in detail elsewhere [15]. The important components for this analysis include the tracking, muon, and time-of-flight (TOF) systems. The tracking system is composed of a silicon-strip vertex detector (SVX) surrounded by an open-cell drift chamber system called the central outer tracker (COT) located inside a solenoid with a 1.4 T magnetic field. The COT and SVX are used for the measurement of charged-particle trajectories and vertex positions. In addition, the COT provides ionization energy loss information, dE/dx, used for particle identification (PID), while the TOF system provides complementary PID information. The muon system is located radially outside the electromagnetic and hadronic calorimeters and consists of two sets of drift chambers and scintillation counters. The central part of the muon system covers the pseudorapidity region $|\eta| \leq 0.6$ and detects muons with $p_T \geq 1.4$ GeV$/c$ [16], and the second part covers the region $0.6 < |\eta| < 1.0$ and detects muons with $p_T \geq 2.0$ GeV$/c$.

In this analysis, $J/\psi \to \mu^+\mu^-$ events are recorded using a dedicated three-level dimuon trigger. The first trigger level requires two muon candidates with matching tracks in the COT and muon systems. The second level applies additional kinematic requirements to the muon pair candidate. The third level requires the invariant mass of the $\mu^+\mu^-$ pair to be within the range of 2.7 to 4.0 GeV$/c^2$.

Offline reconstruction of $B^+ \to J/\psi\phi K^+$ candidates uses only tracks that pass standard CDF quality requirements and which have been corrected for ionization energy loss for the muon or kaon hypothesis, as appropriate. The $B^+ \to J/\psi\phi K^+$ candidates are reconstructed by combining a $J/\psi \to \mu^+\mu^-$ candidate, a $\phi \to K^+K^-$ candidate, and an additional charged track. All five tracks must form a good quality 3D vertex, using *a priori* requirements typical for B hadron reconstruction at CDF [17]. Preliminary event selection requires a J/ψ candidate reconstructed using opposite-sign muon candidates and a ϕ candidate formed from opposite-sign tracks to which we assign the kaon mass. Masses of vector meson candidates must lie within ± 50 MeV$/c^2$ of the J/ψ mass for muons or ± 7 MeV$/c^2$ of the ϕ mass for kaons. In the final B^+ reconstruction the J/ψ is mass constrained, and the B^+ candidates must have $p_T > 4$ GeV$/c$.

To suppress combinatorial background, we use dE/dx and TOF information to identify all three kaons in the final state. The information is summarized in a log-likelihood ratio (LLR), which reflects how well a candidate track can be positively identified as a kaon relative to other hadrons [18]. In addition, we require a minimum $L_{xy}(B^+)$ for the $B^+ \to J/\psi\phi K^+$ candidate, where $L_{xy}(B^+)$ is the projection onto $\vec{p}_T(B^+)$ of the vector connecting the primary vertex to the B^+ decay vertex. The primary vertex is determined for each event using prompt tracks.

The $L_{xy}(B^+)$ and LLR requirements for $B^+ \to J/\psi\phi K^+$ are then chosen to maximize $S/\sqrt{S+B}$, where S is the number of $B^+ \to J/\psi\phi K^+$ signal events and B is the number of background events in the $J/\psi\phi K^+$ mass range of 5.0 to 5.6 GeV$/c^2$ in the data. The values of S and B are determined from an unbinned log-likelihood fit to the mass spectrum of $J/\psi\phi K^+$, for a given set of values of $L_{xy}(B^+)$ and LLR. A Gaussian function is used to represent the $B^+ \to J/\psi\phi K^+$ signal, where the mean value of the Gaussian is fixed to the B^+ world-average mass value [19]. The B^+ mass resolution is fixed to the value 5.9 MeV$/c^2$ obtained from Monte Carlo (MC) simulation [20]. A linear function is used to model the background in the fit. The requirements obtained by maximizing $S/\sqrt{S+B}$ are $L_{xy}(B^+) > 500$ μm and LLR > 0.2. In order to study the efficiency of the $L_{xy}(B^+)$ and LLR selections, we also reconstruct $B^+ \to J/\psi K^+$ and $B_s^0 \to J/\psi\phi$ as control channels. We select approximately 50 000 $B^+ \to J/\psi K^+$ and 3000 $B_s^0 \to J/\psi\phi$ events by applying similar requirements as for the $J/\psi\phi K^+$ channel but without the $L_{xy}(B^+)$ and LLR requirements. The efficiency for PID with the LLR > 0.2 requirement is approximately 80% per kaon and is reasonably flat as a function of kaon p_T; the efficiency for $L_{xy}(B^+) > 500\ \mu$m is approximately 60%, based on the $B^+ \to J/\psi K^+$ control sample.

The invariant mass of $J/\psi\phi K^+$ after the $L_{xy}(B^+)$ and LLR requirements and J/ψ and ϕ mass window requirements is shown in Fig. 1(a). A fit with a Gaussian signal function and a flat background function to the mass spectrum of $J/\psi\phi K^+$ returns a B^+ signal of 75 ± 10(stat) events. We select B^+ signal candidates with a mass within 3σ (17.7 MeV$/c^2$) of the nominal B^+ mass; the purity of the B^+ signal in that mass window is approximately 80%.

The combinatorial background under the B^+ peak includes B hadron decays such as $B_s^0 \to \psi(2S)\phi \to J/\psi\pi^+\pi^-\phi$, in which the pions are misidentified as kaons. However, background events with misidentified kaons cannot yield a Gaussian peak at the B^+ mass consistent with the 5.9 MeV$/c^2$ mass resolution. The kinematics are such that for the hypothesis $B^+ \to J/\psi K^+K^-K^+$, only events with real kaons can produce the observed Gaussian signal. Thus, with the B^+ mass window selection the sample consists of real $B^+ \to J/\psi K^+K^-K^+$ decays over a small combinatorial background.

Figure 1(b) shows the invariant mass distribution of K^+K^- pairs from $\mu^+\mu^-K^+K^-K^+$ candidates within $\pm 3\sigma$ of the nominal B^+ mass. The spectrum shown in this figure has had the sidebands subtracted, but the ϕ mass window selection has not been applied. By fitting the K^+K^- mass spectrum to a P-wave relativistic Breit-Wigner (BW) function [21] convoluted with a Gaussian resolution function with the rms fixed to 1.3 MeV$/c^2$ obtained from simulation, we obtain a mass of 1019.6 ± 0.3 MeV$/c^2$ and a width of 3.84 ± 0.65 MeV$/c^2$ with χ^2 probability of 28%, consistent with the world-average values for the ϕ meson [19]. The good fit indicates that after the ± 7 MeV$/c^2$ selection on the ϕ mass window, the $B^+ \to J/\psi K^+K^-K^+$ final state is well described as $J/\psi\phi K^+$, with negligible contributions from $J/\psi f_0(980)K^+$ or $J/\psi K^+K^-K^+$ phase space.

We examine the effects of detector acceptance and selection requirements using $B^+ \to J/\psi\phi K^+$ MC events simulated by phase space distributions. The MC events are smoothly distributed in the Dalitz plot and in the $J/\psi\phi$ mass spectrum. Figure 2(a) shows the Dalitz plot of $m^2(\phi K^+)$ versus $m^2(J/\psi\phi)$, and Fig. 2(b) shows the mass difference, $\Delta M = m(\mu^+\mu^-K^+K^-) - m(\mu^+\mu^-)$, for events in the B^+ mass window in our data sample. We examine the enhancement in the ΔM spectrum just above $J/\psi\phi$ threshold, using 73 events with $\Delta M < 1.56$ GeV$/c^2$. We exclude the high mass part of the spectrum to avoid combinatorial backgrounds from misidentified $B_s^0 \to \psi(2S)\phi \to (J/\psi\pi^+\pi^-)\phi$ decays.

We model the enhancement by an S-wave relativistic BW function [22] convoluted with a Gaussian resolution function with the rms fixed to 1.7 MeV$/c^2$ obtained from MC calculations, and use three—body phase space [19] to describe the background shape. An unbinned likelihood fit to the ΔM distribution, as shown in Fig. 2(b), returns a yield of 14 ± 5 events, a ΔM of 1046.3 ± 2.9 MeV$/c^2$, and a width of $11.7^{+8.3}_{-5.0}$ MeV$/c^2$. We also fit the ΔM distribution to a single Gaussian with rms given by the mass resolution (1.7 MeV$/c^2$), plus phase space background, to test the hypothesis that the structure has zero width. The statistical significance for a nonzero width determined by the log-likelihood ratio between these two fits is 3.4σ, indicating a strong decay for this structure.

We use the log-likelihood ratio of $-2\ln(\mathcal{L}_0/\mathcal{L}_{\max})$ to determine the significance of the structure at the $J/\psi\phi$ threshold, where $\mathcal{L}_0$ and $\mathcal{L}_{\max}$ are the likelihood values for

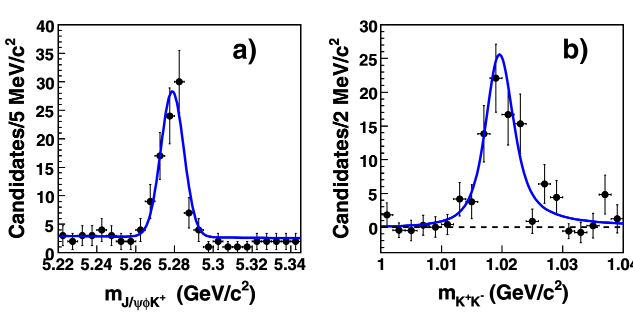

FIG. 1 (color online). (a) The mass distribution of $J/\psi\phi K^+$; the solid line is a fit to the data with a Gaussian signal function and flat background function. (b) The B^+ sideband-subtracted mass distribution of K^+K^- without the ϕ mass window requirement. The solid curve is a P-wave relativistic Breit-Wigner fit to the data.

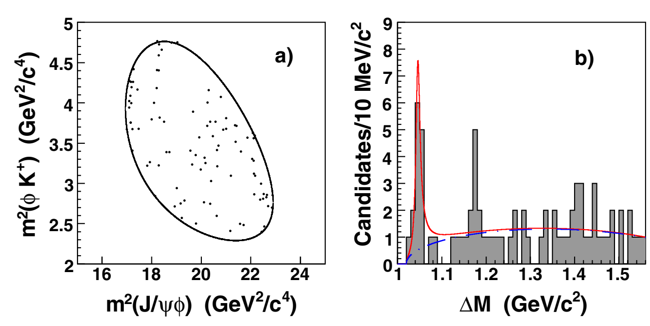

FIG. 2 (color online). (a) The Dalitz plot of $m^2(\phi K^+)$ versus $m^2(J/\psi\phi)$ in the B^+ mass window. The boundary shows the kinematic allowed region. (b) The mass difference, ΔM, between $\mu^+\mu^-K^+K^-$ and $\mu^+\mu^-$, in the B^+ mass window. The dash-dotted curve is the background contribution and the red solid curve is the total unbinned fit.

the null hypothesis fit and signal hypothesis fit. The $\sqrt{-2\ln(\mathcal{L}_0/\mathcal{L}_{\max})}$ value is 5.3 for a pure three-body phase space background shape assumption. To estimate the probability that background fluctuations alone would give rise to signals as significant as that seen in the data, we simulate ΔM spectra based on the background distribution alone, and search for the most significant fluctuation in each spectrum in the mass range of 1.02 to 1.56 GeV/c^2, with widths in the range of 1.7 (resolution) to 120 MeV/c^2 (10 times of the observed width). From these spectra we obtain the distribution for the quantity $-2\ln(\mathcal{L}_0/\mathcal{L}_{\max})$ in pure background samples, and compare this with the signal in the data. We performed a total of 3.1×10^6 simulations and found 29 trials with a $-2\ln(\mathcal{L}_0/\mathcal{L}_{\max})$ value greater than or equal to the value obtained in the data. The resulting p-value is 9.3×10^{-6}, corresponding to a significance of 4.3σ. Thus, the significance is decreased from a simple estimate of 5.3σ to 4.3σ by taking into account the absence of a prior prediction for the mass and width [23].

In the analysis described above, we assumed that the backgrounds to the BW signal from both $B^+ \to J/\psi\phi K^+$ decays and combinatorial events in the B^+ mass window are described by three-body phase space. After making the $\Delta M < 1.56\ \text{GeV}/c^2$ selection, we perform a fit to the $J/\psi\phi K^+$ mass spectrum with a Gaussian B^+ signal and an empirical linear background shape; from this fit we determine that the 73 events within the final B^+ mass window include 15 ± 1 combinatorial background events by scaling it from the entire $J/\psi\phi K^+$ mass range. We model the B^+ events using three-body phase space as above, but use a flat spectrum to describe the combinatorial events. This increases the average background level at small ΔM and reduces the yield by one event. The $\sqrt{-2\ln(\mathcal{L}_0/\mathcal{L}_{\max})}$ value with this modeling of background is 4.8. We performed a total of 1.1×10^6 simulations and found 99 trials with a $-2\ln(\mathcal{L}_0/\mathcal{L}_{\max})$ value greater than or equal to the value we obtained in the data. The p-value determined by this MC simulation is 9.0×10^{-5}, about 3.8σ significance.

The mass of this structure is $4143.0 \pm 2.9\ \text{MeV}/c^2$ after including the world-average J/ψ mass. To study the systematic uncertainties of the mass and width, we repeat the fit to the ΔM distribution while varying the background shapes as described above, and separately switching to a nonrelativistic BW function for a signal. The largest deviation from the nominal values are 1.2 MeV/c^2 for ΔM and 3.7 MeV/c^2 for the width. Therefore we assign a systematic uncertainty of 1.2 MeV/c^2 to the mass and 3.7 MeV/c^2 to the width.

There is a small cluster of events approximately one pion mass higher than the first structure, located around 1.18 GeV/c^2 in Fig. 2(b). However, the statistical significance of this cluster is less than 3σ. To investigate possible reflections, we examine the Dalitz plot and projections into ϕK^+ and $J/\psi K^+$ spectrum. We find no evidence for any other structure in the ϕK^+ and $J/\psi K^+$ spectrum; the only structure [i.e. $K_2(1770)$] that has been claimed in the ϕK^+ spectrum by previous experiments is too broad to alter our analysis [24].

In summary, the large sample of $B^+ \to J/\psi\phi K^+$ decays (75 events) enables us to search for structure in the $J/\psi\phi$ mass spectrum, and we find evidence for a narrow structure near the $J/\psi\phi$ threshold with a significance in excess of 3.8σ. Assuming an S-wave relativistic BW signal, the mass and width of this structure, including systematic uncertainties, are measured to be $4143.0 \pm 2.9(\text{stat}) \pm 1.2(\text{syst})\ \text{MeV}/c^2$ and $11.7^{+8.3}_{-5.0}(\text{stat}) \pm 3.7(\text{syst})\ \text{MeV}/c^2$, respectively. It is well above the threshold for open charm decays, so a $c\bar{c}$ charmonium meson with this mass would be expected to decay into an open charm pair dominantly and to have a tiny branching fraction into $J/\psi\phi$ [5]. Thus, this structure does not fit conventional expectations for a charmonium state. We note that this structure decays to $J/\psi\phi$ just above the $J\psi\phi$ threshold, similar to the $Y(3930)$ [2], which decays to $J/\psi\omega$ near the $J/\psi\omega$ threshold. We therefore term it $Y(4140)$.

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