Search for $B^0 \to J/\psi\phi$ Decays

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We report a search for the decay $B^0 \to J/\psi \phi$, using a sample of $657 \times 10^6$ $B\bar{B}$ pairs collected with the Belle detector at the $\Upsilon(4S)$ resonance. No statistically significant signal is found and an upper limit for the branching fraction is determined to be $\mathcal{B}(B^0 \rightarrow J/\psi\phi) < 9.4 \times 10^{-7}$ at 90% confidence level.

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Studies of exclusive $B$ meson decays to charmonium play an important role in exploring $CP$ violation\cite{1} and establishing the Kobayashi-Maskawa anzatz\cite{2} for $CP$ violation in the Standard Model. Such studies have also resulted in observations of new resonant states that include a $(c\bar{c})$ pair\cite{3,4,5}. The decay $B^0 \rightarrow J/\psi\phi$ is expected to proceed mainly via a Cabibbo-suppressed and color-suppressed transition ($b \rightarrow c\bar{d}d$) with rescattering, as shown in Fig. 1. In $B$ decays, effects presumably due to rescattering have been seen in various decay processes. For example, the large branching fractions observed for $B^0 \rightarrow D_s^- K^+$\cite{6} and $B^- \rightarrow \chi_c^0 K^-$\cite{7} decays can be attributed to rescattering processes\cite{8,9}. An isospin analysis on $B \rightarrow DK^{(*)}$ decays indicates significant final state rescattering effects\cite{10}. Final state rescattering may play an important role in understanding patterns of $CP$ asymmetries in $B$ decays to two charmless pseudoscalars\cite{11}. Studies of $B$ decays such as $B^0 \rightarrow J/\psi \phi$, which would proceed mainly via rescattering, provide useful information for understanding rescattering mechanisms. Previously, the BaBar collaboration reported a search for this decay mode and set an upper limit for the branching fraction $B < 9.2 \times 10^{-6}$ at the 90% confidence level based on $56 \times 10^6$ $B\bar{B}$ pairs\cite{12}.

![Quark-level diagram for $B^0 \rightarrow J/\psi \phi$ decay](image)

FIG. 1: Quark-level diagram for $B^0 \rightarrow J/\psi \phi$ decay

In this paper, we report the results of a search for the decay mode $B^0 \rightarrow J/\psi \phi$ using the Belle detector\cite{13} at the KEKB energy-asymmetric $e^+e^-$ collider\cite{14} based on a 605 fb$^{-1}$ data sample containing $657 \times 10^6$ $B\bar{B}$ pairs. This sample is more than an order of magnitude larger than that used previously.

The Belle detector is a large-solid-angle magnetic spectrometer that consists of a silicon vertex detector (SVD), a 50-layer central drift chamber (CDC), an array of aerogel threshold Cherenkov counters (ACC), a barrel-like arrangement of time-of-flight scintillation counters (TOF), and an electromagnetic calorimeter comprised of CsI(Tl) crystals (ECL). These detectors are located inside a superconducting solenoid that provides a 1.5 T magnetic field. An iron flux-return located outside of the coil is instrumented to detect $K_L^0$ mesons and to identify muons (KLM).

Events are required to pass a basic hadronic event selection\cite{15}. To suppress continuum background ($e^+e^- \rightarrow q\bar{q}$, where $q = u,d,s,c$), we require the ratio of the second to zeroth Fox-Wolfram moments\cite{16} to be less than 0.5.

Candidates for $B^0 \rightarrow J/\psi \phi$ decays are reconstructed from the decays $J/\psi \rightarrow \ell^+\ell^-(\ell = e,\mu)$ and $\phi \rightarrow K^+ K^-$. The selection criteria for the $J/\psi$ decaying to $\ell^+\ell^-$ are identical to those used in our previous papers\cite{17}. $J/\psi$ candidates are pairs of oppositely charged tracks that originate from a region within 5 cm of the nominal interaction point (IP) along the beam direction and are positively identified as leptons. In order to reduce the effect of bremsstrahlung or final-state radiation, photons detected in the ECL within 0.05 radians of the original $e^+$ or $e^-$ direction are included in the calculation of the $e^+e^-(\gamma)$ invariant mass. Because of the radiative low-mass tail, the $J/\psi$ candidates are required to be within an asymmetric invariant mass window: $-150 (-60)$ MeV/$c^2$ $< M_{e^+e^-}(M_{\mu^+\mu^-}) - m_{J/\psi} < +36 (+36)$ MeV/$c^2$, where $m_{J/\psi}$ is the nominal $J/\psi$ mass\cite{17}. In order to improve the $J/\psi$ momentum resolution, a vertex and mass constrained fit to the reconstructed $J/\psi$ candidates is then performed and a loose cut on the vertex fit quality is applied.

In order to identify hadrons, a likelihood $L_i$ for each
hadron type \( i \) \( (i = \pi, K \text{ and } p) \) is formed using information from the ACC, the TOF, and \( dE/dx \) measurements from the CDC. Kaons from the \( \phi \) meson are selected with the requirement \( L_K/(L_K + L_\pi) > 0.7 \), which has an efficiency of 90.0% and a 5.9% probability to misidentify a pion as kaon. This requirement is chosen to minimize the upper limit expected in the absence of a real signal, based on studies of signal and background Monte Carlo (MC) events. We reconstruct \( \phi \) candidates from pairs of \( K^+K^- \) candidates, where we require the invariant mass to be within \( \pm 10 \) MeV/\( c^2 \) of the nominal \( \phi \) mass \[17\].

\( B^0 \) mesons are reconstructed by combining a \( J/\psi \) with a \( \phi \) candidate. We identify \( B^0 \) candidates using two kinematic variables calculated in the center-of-mass system: the beam-energy constrained mass \( (M_{bc} \equiv \sqrt{E_{\text{beam}} - P_B^2}) \) and the energy difference \( (\Delta E \equiv E_B - E_{\text{beam}}) \), where \( E_{\text{beam}} \) is the beam energy, and \( P_B \) and \( E_B \) are the reconstructed momentum and energy of the \( B^0 \) candidate. We select \( B \) candidates within the range \(-0.2 \) GeV < \( \Delta E \) < 0.3 GeV and 5.27 GeV/\( c^2 \) < \( M_{bc} \) < 5.29 GeV/\( c^2 \) for the final analysis. After all selection requirements, about 4.9% of the events contain more than one \( B^0 \) candidate. For these events, we choose the \( B \) candidate whose daughter particle \( \phi \) mass is closest to the nominal value. Finally, a total of 85 candidates are selected.

The dominant background comes from \( B\bar{B} \) events with \( B \) decays to \( J/\psi \). We use a MC sample corresponding to 3.86 \times 10^{10} generic \( B \bar{B} \) decays that includes all known \( B \to J/\psi X \) processes to investigate these backgrounds. We find that the dominant backgrounds come from \( B^0 \to J/\psi K^{*0}(892)[\to K^- \pi^+] \) and \( B^0/\bar{B} \to J/\psi K_1(1270)[\to K^- \pi^+ \pi^0/\pi^-] \) \[18\]. In both cases, a pion is misidentified as a kaon, and in the latter case, the other pion is missed. The former has a peak at \( \Delta E \sim 0.1 \) GeV, while the latter has a broad peak in the negative \( \Delta E \) region. The remaining background is due to random combinations of \( J/\psi \) and \( \phi \) candidates and does not peak in the \( \Delta E \) distribution (referred to as combinatorial background).

The signal yield is extracted by performing an unbinned extended maximum-likelihood fit to the \( \Delta E \) distribution of candidate events. The likelihood function is given as

\[
\mathcal{L} = \frac{e^{-y}}{N!} \prod_{i=1}^{N} \left( \sum_{k} N_k \times P_k(\Delta E^i) \right),
\]

where \( N \) is the total number of candidate events, \( i \) is the identifier of the \( i \)-th event, \( N_k \) and \( P_k \) are the yield and probability density function (PDF) of the component \( k \), which corresponds to the signal, \( J/\psi K_1 \), \( J/\psi K^{*0} \), and combinatorial backgrounds.

The signal PDF is modeled by a sum of two Gaussians. The background PDFs are two Gaussians for the \( J/\psi K_1 \) component, a bifurcated Gaussian for the \( J/\psi K^{*0} \) component and a second-order polynomial for combinatorial background, respectively. The parameters of these PDFs are determined from MC simulations. We use \( B^0 \to J/\psi K^{*0} \) decay with \( K^{*0} \to K^- \pi^+ \) as a control data sample to correct for small differences between data and MC in the mean and width of the signal PDF. The \( J/\psi K_1 \) component shape is verified by comparing data and MC events in the \( K^+K^- \) mass sideband region (1.04 – 1.10 GeV/\( c^2 \)), while events in the 5.22 GeV/\( c^2 \) < \( M_{bc} \) < 5.26 GeV/\( c^2 \) and \( K^+K^- \) mass sideband region are used to check the combinatorial background shape. Possible differences between data and MC are included in the systematic errors.

| TABLE I: Summary of the results: upper limits are at the 90% confidence level. |
|-----------------|-----------------|-----------------|
| Signal yield    | 4.6 \( ^{+7.1}_{-2.5} \) |
| Significance    | 2.3\( \sigma \) |
| Upper limit of signal yield (\( Y_{90} \)) | 9.5 |
| Detection efficiency (\( \epsilon \)) | 26.2% |
| Upper limit of branching fraction | \( < 9.4 \times 10^{-7} \) |

In the fit, all \( N_k \) values are free parameters. Figure 2 shows the \( \Delta E \) distribution of the \( B^0 \to J/\psi \phi \) candidates together with the fit result. We obtain a signal yield of 4.6 \( ^{+3.1}_{-2.5} \) events with a statistical significance of 2.3\( \sigma \). This statistical significance is defined as \( \sqrt{-2 \ln(L_0/L_{\text{max}})} \), where \( L_{\text{max}} \) and \( L_0 \) denote the maximum likelihood with the fitted signal yield and with the yield fixed to zero, respectively. The number of misidentified \( B^0 \to J/\psi K^{*0} \) events obtained from the fit is 22.5 \( ^{+5.4}_{-4.8} \) and is consistent with the expectation obtained from MC simulation incorporating the misidentification probability and the world average branching fraction \[17\].

As no significant signal is found for the \( B^0 \to J/\psi \phi \) decay mode, we obtain an upper limit on the yield at the 90% confidence level (\( Y_{90} \)) by a frequentist method using ensembles of pseudo-experiments. For a given signal yield, 10000 sets of signal and background events are generated according to the PDFs, and fits are performed. The confidence level is obtained as the fraction of samples that give a fit yield larger than that of data (4.6). We account for systematic error by smearing the fit yield by the total systematic error described below. We scan signal yields and obtain \( Y_{90} = 9.5 \).

The corresponding branching fraction upper limit is determined with

\[
B \lessdot \frac{\epsilon \times N_{BB} \times B(J/\psi \to \ell^+\ell^-) \times B(\phi \to K^+K^-)}{Y_{90}}
\]

Here \( N_{BB} \) is the number of \( B\bar{B} \) pairs, and we use the world averages \[17\] for the branching fractions of \( B(J/\psi \to \ell^+\ell^-) \) and \( B(\phi \to K^+K^-) \). The efficiency (\( \epsilon \) = 26.2%) is determined from a signal MC sample with the same selection as used for the data, where a correc-
FIG. 2: $\Delta E$ distribution for $B^0 \to J/\psi \phi$ candidates. The curves show the signal (red dashed) and the background components (cyan dashed for $J/\psi K_1$, magenta dot-dashed for $J/\psi K^{*0}$ and green triple-dot dashed for combinatorial) as well as the overall fit (blue solid curve).

The sources and sizes of systematic uncertainties are summarized in Tables II and III. The dominant sources of systematic error in the reconstruction efficiency are tracking efficiency and particle identification. Uncertainties in the tracking efficiency are estimated by linearly summing the momentum-dependent single track systematic errors ($\sim 1\%$ per track). We use control samples of $J/\psi \to \ell^+\ell^-$ and $e^+e^- \to e^+e^-\ell^+\ell^-$ events to estimate lepton identification efficiency corrections and uncertainties. For the $J/\psi \to \mu^+\mu^-$ mode, we find the efficiency for a muon track in the data to be $(4.3 \pm 3.1)\%$ lower than that of MC simulation. We correct the efficiency for this difference and assign a 3.1% uncertainty per muon track. For the $J/\psi \to e^+e^-$ mode, the difference between efficiencies in the data and in the MC simulation is small, and we assign a 2.7% uncertainty per electron track based on their difference and errors. We assign an uncertainty of 1.2% per kaon track, which is obtained using kinematically identified kaons in a $D^{*+} \to D^0\pi^+[D^0 \to K^-\pi^+]$ sample. Because of the small energy release in $\phi \to K^+K^-$ decay, the selection efficiency of $B^0 \to J/\psi \phi$ decays depends only weakly on the final state polarization. We use an average of the efficiencies for fully longitudinally and transversely polarized cases and assign the difference as a systematic error ($\pm 2.6\%$ including MC statistical error). The systematic errors due to signal and background shapes are evaluated by varying each of the PDF parameters by its uncertainty. We find that the $J/\psi K_1$ component uncer-
tainty is dominant and that the total systematic error on the signal yield is $+21.7\% / -26.1\%$ (Table III). Adding all sources in quadrature and conservatively taking the larger of the asymmetric errors, the total systematic error is estimated to be 27%. As a cross check of the MC efficiency and analysis procedure, we apply the same analysis procedure to the $B^0 \rightarrow J/\psi K^{*0}$ control sample and obtain $B = (1.24 \pm 0.01) \times 10^{-3}$ (the error is statistical only). This is consistent with the world average within its uncertainty and the estimated systematic error of the efficiency mentioned above.

In summary, we have searched for $B^0 \rightarrow J/\psi \phi$ decays. No statistically significant signal is found and an upper limit for this decay is determined to be $B(B^0 \rightarrow J/\psi \phi) < 9.4 \times 10^{-7}$ at the 90% confidence level. This result improves upon the previous result by about a factor of 10 and imposes a more stringent constraint on rescattering effects in $B^0 \rightarrow J/\psi \phi$ decays.

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