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## Rare $B$ Decays into States Containing a $J/\psi$ Meson and a Meson with $s\bar{s}$ Quark Content

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We report a study of the  $B$  meson decays,  $B^+ \rightarrow J/\psi\phi K^+$ ,  $B^0 \rightarrow J/\psi\phi K_S^0$ ,  $B^0 \rightarrow J/\psi\phi$ ,  $B^0 \rightarrow J/\psi\eta$ , and  $B^0 \rightarrow J/\psi\eta'$  using  $56 \times 10^6$   $B\bar{B}$  events collected at the  $\Upsilon(4S)$  resonance with the BABAR detector at the PEP-II  $e^+e^-$  asymmetric-energy storage ring. We measure the branching fractions  $\mathcal{B}(B^+ \rightarrow J/\psi\phi K^+) = (4.4 \pm 1.4(\text{stat}) \pm 0.5(\text{syst})) \times 10^{-5}$  and  $\mathcal{B}(B^0 \rightarrow J/\psi\phi K_S^0) = (5.1 \pm 1.9(\text{stat}) \pm 0.5(\text{syst})) \times 10^{-5}$ , and set upper limits at 90% confidence level for the branching fractions  $\mathcal{B}(B^0 \rightarrow J/\psi\phi) < 9.2 \times 10^{-6}$ ,  $\mathcal{B}(B^0 \rightarrow J/\psi\eta) < 2.7 \times 10^{-5}$ , and  $\mathcal{B}(B^0 \rightarrow J/\psi\eta') < 6.3 \times 10^{-5}$ .

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The observation [1] of  $CP$  violating  $B$  meson decays into  $CP$  eigenstates with charmonium provides major evidence for the Cabibbo-Kobayashi-Maskawa model [2] and an important advance in our understanding of the standard model. This motivates the search for additional  $CP$  eigenstate decay modes of neutral  $B$  mesons to enable new  $CP$  tests of the standard model.

Recent observations of the  $B$  meson decays  $B \rightarrow J/\psi\pi$  [3] and  $J/\psi\rho$  [4] indicate the Cabibbo-suppressed transitions  $b \rightarrow c\bar{c}d$  via the color-suppressed diagram shown in Fig. 1(a). Here we present a search for similar color-suppressed modes except with hidden strangeness,  $s\bar{s}$ , in the final state:  $B \rightarrow J/\psi\eta$ ,  $J/\psi\eta'$ ,  $J/\psi\phi$ , and  $J/\psi\phi K$ . The decays  $B^0 \rightarrow J/\psi\eta$  and  $B^0 \rightarrow J/\psi\eta'$  occur via the

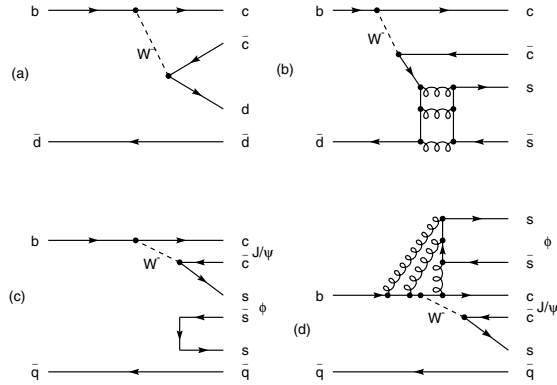


FIG. 1. Quark diagrams: (a) Tree diagram for  $B \rightarrow J/\psi \pi$  and  $J/\psi \rho$ , (b) rescattering for  $B \rightarrow J/\psi \phi$ , (c) strange sea quarks, and (d) gluon coupling for  $B \rightarrow J/\psi \phi K$ .

same diagram, Fig. 1(a), and should have a comparable rate. If large enough samples can be isolated, these  $CP$  eigenstates could be used to test  $CP$  violation [5]. Models based on the heavy quark factorization approximation by Deandrea *et al.* [6] are used to predict that the branching fraction for  $B^0 \rightarrow J/\psi \eta$  is a factor of 4 smaller than that for  $B^0 \rightarrow J/\psi \pi^0$ . The decay  $B^0 \rightarrow J/\psi \phi$  is likely a color-suppressed mode with rescattering as shown in Fig. 1(b), so its absence would indicate that the rescattering effects are negligible. The decay  $B \rightarrow J/\psi \phi K$  is a Cabibbo-allowed and color-suppressed decay via the transition  $b\bar{q} \rightarrow c\bar{s}s\bar{s}q$ , where the  $s\bar{s}$  quark pairs are produced from sea quarks or are connected via gluons as shown in Figs. 1(c) and 1(d), respectively. This particular three-body decay may be of interest in the search for hybrid charmonium states that decay to the final state  $J/\psi \phi$  [7]. In this Letter, we report on branching fractions or upper limits for  $J/\psi \eta$ ,  $J/\psi \eta'$ ,  $J/\psi \phi$ ,  $J/\psi \phi K^+$ , and  $J/\psi \phi K_S^0$ .

The data used in this analysis were collected at the PEP-II asymmetric-energy  $e^+e^-$  storage ring with the BABAR detector, fully described elsewhere [8] with a brief overview in [3]. The BABAR detector contains a silicon vertex tracker and a drift chamber in a 1.5-T solenoidal magnetic field to detect charged particles and measure their momentum and energy loss. Photons and neutral hadrons are detected in a CsI(Tl) calorimeter. An internally reflecting ring-imaging Cherenkov detector is used for charged particle identification (PID). Penetrating muons and neutral hadrons are identified by the steel flux return.

The data correspond to a total integrated luminosity of  $50.9 \text{ fb}^{-1}$  taken on the  $Y(4S)$  resonance and  $6.3 \text{ fb}^{-1}$  taken off resonance at an energy 0.04 GeV below the  $Y(4S)$  mass and below the threshold for  $B\bar{B}$  production. In this sample, there are  $(55.5 \pm 0.6) \times 10^6$   $B\bar{B}$  events ( $N_{B\bar{B}}$ ).

In this analysis, the charged track selection requirements and the selection of photon, electron, and muon candidates use the methods from previous publications

TABLE I. Mass regions for selection of intermediate particles.

| Mode                               | Mass range ( $\text{GeV}/c^2$ ) |   |                              |
|------------------------------------|---------------------------------|---|------------------------------|
| $J/\psi \rightarrow e^+e^-$        | 2.95                            | < | $M(e^+e^-)$ < 3.14           |
| $J/\psi \rightarrow \mu^+\mu^-$    | 3.06                            | < | $M(\mu^+\mu^-)$ < 3.14       |
| $\phi \rightarrow K^+K^-$          | 1.004                           | < | $M(K^+K^-)$ < 1.034          |
| $K_S^0 \rightarrow \pi^+\pi^-$     | 0.489                           | < | $M(\pi^+\pi^-)$ < 0.507      |
| $\eta \rightarrow \gamma\gamma$    | 0.529                           | < | $M(\gamma\gamma)$ < 0.565    |
| $\eta \rightarrow \pi^+\pi^-\pi^0$ | 0.529                           | < | $M(\pi^+\pi^-\pi^0)$ < 0.565 |
| $\eta' \rightarrow \eta\pi^+\pi^-$ | 0.938                           | < | $M(\eta\pi^+\pi^-)$ < 0.978  |
| $\pi^0 \rightarrow \gamma\gamma$   | 0.120                           | < | $M(\gamma\gamma)$ < 0.150    |

[9], and the selection of kaon and pion candidates follows [10].

The intermediate states in this analysis,  $J/\psi(ee, \mu\mu)$ ,  $\phi(K^+K^-)$ ,  $\eta(\gamma\gamma, \pi^+\pi^-\pi^0)$ ,  $\eta'[\eta(\gamma\gamma)\pi^+\pi^-]$ ,  $\pi^0(\gamma\gamma)$ , and  $K_S^0(\pi^+\pi^-)$ , are selected with the mass intervals in Table I. Since  $B^0 \rightarrow J/\psi \eta$  and  $B^0 \rightarrow J/\psi \eta'$  involve decays of a pseudoscalar meson into a vector and a pseudoscalar meson, the angular distribution is proportional to  $\sin^2\theta_\ell$ , where  $\theta_\ell$  is the helicity angle [3] of the lepton from the  $J/\psi$ . Hence, an additional requirement of  $|\cos\theta_\ell| < 0.8$  is applied to reject continuum and other backgrounds. The  $\eta$  candidates are rejected if either of the associated photons, in combination with any other photon in the event, forms a  $\gamma\gamma$  mass within  $20 \text{ MeV}/c^2$  of the  $\pi^0$  mass. For the mode  $B^0 \rightarrow J/\psi \eta(\gamma\gamma)$ , the  $\eta$  candidate is required to have  $|\cos\theta_\eta^\eta| < 0.8$ , where  $\theta_\eta^\eta$  is the photon helicity angle in the  $\eta$  rest frame. This rejects combinatoric background due to random pairs of photons that typically have a photon helicity angle that peaks at  $0^\circ$  or  $180^\circ$ . For the  $\eta' \rightarrow \eta(\gamma\gamma)\pi^+\pi^-$  candidates, we use the same  $\eta$  selection criteria for the  $\eta$  described above, including the  $\pi^0$  veto.

An additional requirement separates two-jet continuum events from the more spherical  $B$  meson decays. The angle  $\theta_T$  between the thrust [3] direction of the  $B$  meson candidate and the thrust direction of the remaining tracks in the event is calculated. We require  $|\cos\theta_T| < 0.8$ , since these thrust axes are uncorrelated and the distribution in  $\cos\theta_T$  is flat for  $B\bar{B}$  events, while the distribution is peaked at  $\cos\theta_T = \pm 1$  for continuum events.

The intermediate candidates are combined to construct the  $B$  candidates for the six decay modes under study. The estimation of the signal and the background employs two kinematic variables: the energy difference  $\Delta E$  between the energy of the  $B$  candidate and the beam energy  $E_b^*$  in the  $Y(4S)$  rest frame; and the energy-substituted mass  $m_{ES} = \sqrt{(E_b^*)^2 - (P_B^*)^2}$ , where  $P_B^*$  is the reconstructed momentum of the  $B$  candidate in the  $Y(4S)$  frame. Typically, these two weakly correlated variables form a two-dimensional Gaussian distribution for the  $B$  meson signal but not for background. The resolutions in  $\Delta E$  and

TABLE II. Branching fractions and 90% C.L. upper limits.

| Mode                          | Signal region       |                                   | Efficiency | $n_0$ | $n_b \pm \sigma_b$ | $N_{90\%}$ | $P$ value                   | 90% C.L.U.L.<br>( $10^{-5}$ ) | Branching fraction<br>( $10^{-5}$ ) |
|-------------------------------|---------------------|-----------------------------------|------------|-------|--------------------|------------|-----------------------------|-------------------------------|-------------------------------------|
|                               | $\Delta E$<br>(MeV) | $ m_{ES} - m_B $<br>(MeV/ $c^2$ ) |            |       |                    |            |                             |                               |                                     |
| $J/\psi\phi K^+$              | 57.0                | 8.0                               | 10.6%      | 23    | $7.8 \pm 0.6$      |            | $(0.77-2.4) \times 10^{-5}$ |                               | $4.4 \pm 1.4 \pm 0.5$               |
| $J/\psi\phi K_S^0$            | 57.0                | 8.0                               | 8.6%       | 13    | $3.3 \pm 0.4$      |            | $(4.2-13) \times 10^{-5}$   |                               | $5.1 \pm 1.9 \pm 0.5$               |
| $J/\psi\phi K^0$              |                     |                                   |            |       |                    |            |                             |                               | $10.2 \pm 3.8 \pm 1.0$              |
| $J/\psi\phi$                  | 57.0                | 8.0                               | 12.1%      | 1     | $0.3 \pm 0.2$      | 3.60       |                             | <0.9                          | $0.18 \pm 0.26 \pm 0.03$            |
| $J/\psi\eta'$                 | 100.0               | 10.0                              | 2.5%       | 0     | $0.5 \pm 0.3$      | 1.81       |                             | <6.3                          | $-1.7 \pm 1.0 \pm 0.2$              |
| $J/\psi\eta(\gamma\gamma)$    | 100.0               | 10.0                              | 15.5%      | 8     | $1.7 \pm 0.4$      | 11.5       | $(3.9-15) \times 10^{-4}$   | <2.9                          | $1.6 \pm 0.7 \pm 0.2$               |
| $J/\psi\eta(\pi^+\pi^-\pi^0)$ | 72.0                | 10.0                              | 8.7%       | 4     | $1.5 \pm 0.9$      | 6.76       | $(0.66-2.2) \times 10^{-1}$ | <5.1                          | $1.9 \pm 1.7 \pm 0.2$               |
| $J/\psi\eta$ combined         |                     |                                   |            |       |                    |            | $(2.6-33) \times 10^{-5}$   | <2.7                          | $1.6 \pm 0.6 \pm 0.1$               |

$m_{ES}$  are decay mode dependent. A signal region for each mode is defined as a rectangular region in the  $\Delta E$  versus  $m_{ES}$  plane (Table II). The  $m_{ES}$  range is given in terms of  $m_{ES} - m_B$ , where  $m_B$  is the mass of  $B$  meson. The number of data events,  $n_0$ , observed in the signal region for each mode is listed in Table II.

The efficiencies for each mode are determined by Monte Carlo simulation. The simulations of  $J/\psi\phi K$  and  $J/\psi\phi$  decays assumed three- and two-body phase space, respectively, with unpolarized  $J/\psi$  and  $\phi$  decays. The  $J/\psi\eta$  and  $J/\psi\eta'$  simulations used the angular correlations determined by the helicity amplitude [11].

The backgrounds in the  $m_{ES}$  distribution have two components: a combinatoric background, whose shape is described by an ARGUS function [12], and a peaking background that peaks in the signal region and is described by a Gaussian function. The sources of combinatoric background are the continuum events and two categories of  $B\bar{B}$  events: decays with a leptonic  $J/\psi$  decay, and those without. Monte Carlo simulation studies show that the source of the peaking background is  $B\bar{B}$  events that contain a leptonic  $J/\psi$  decay.

The shape of the ARGUS function is determined mode by mode by fitting to a simulated  $m_{ES}$  distribution formed from data event candidates using the same selection except negating the normal lepton identification.

The normalization of the combinatoric background for each mode is obtained from a fit to the  $m_{ES}$  distributions in the  $\Delta E$  signal region of the on-peak data. The integral of the ARGUS function in the signal region is  $n_C$ , the number of combinatoric background events.

The peaking background is determined from a fit to the  $m_{ES}$  distribution of Monte Carlo  $B\bar{B}$  events with leptonic  $J/\psi$  decays using the sum of a Gaussian and an ARGUS function. The number of peaking background events  $n_p$  is the integral of the Gaussian function in the signal region.

The total number of background events ( $n_b$ ) and the uncertainty on this number ( $\sigma_b$ ) listed in Table II are calculated from the fit value of  $n_C$  and  $n_p$  and their errors. The combinatoric background is by far the dominant background in all modes except the  $B^0 \rightarrow J/\psi\eta(\pi^+\pi^-\pi^0)$  mode, where the peaking component is  $\sim 20\%$  of the total background.

Table III lists the systematic error from the uncertainty on each of the following:  $N_{B\bar{B}}$ ; secondary branching fractions [13]; Monte Carlo statistics; PID, tracking, and photon detection efficiencies, which are based on the study of control samples; and background parametrization, which is estimated using  $\Delta E$  sideband information.

Additional systematic uncertainties due to the decay model dependence are estimated for the modes  $J/\psi\phi$ ,  $J/\psi\phi K^+$ , and  $J/\psi\phi K_S^0$ . Monte Carlo simulations are used to determine how the efficiency depends on assumptions about intermediate resonances and angular distributions. Two samples are generated for each of the three modes with decay distributions determined by the assumed polarization of the vector daughter mesons, rather than by phase space. One sample is generated with 100% transversely polarized  $J/\psi$  and  $\phi$  mesons, and the other with 100% longitudinally polarized  $J/\psi$  and  $\phi$  mesons. The resulting relative change in efficiency is entered as a

TABLE III. Systematic error summary on the branching fractions. All are fractional uncertainties in percent.

| Mode                          | $N_{B\bar{B}}$ | Secondary branching fractions | Monte Carlo statistics | PID, tracking, photon detection | Background parametrization | Model | Total |
|-------------------------------|----------------|-------------------------------|------------------------|---------------------------------|----------------------------|-------|-------|
| $J/\psi\phi K^+$              | 1.1            | 2.2                           | 1.6                    | 8.2                             | 5.9                        | 0.4   | 10.4  |
| $J/\psi\phi K_S^0$            | 1.1            | 2.2                           | 2.1                    | 8.3                             | 1.9                        | 0.9   | 9.3   |
| $J/\psi\phi$                  | 1.1            | 2.2                           | 1.6                    | 6.7                             | 12.0                       | 1.0   | 14.1  |
| $J/\psi\eta'$                 | 1.1            | 3.8                           | 4.6                    | 9.3                             | 7.1                        | ...   | 13.3  |
| $J/\psi\eta(\gamma\gamma)$    | 1.1            | 1.8                           | 1.6                    | 6.0                             | 6.9                        | ...   | 9.5   |
| $J/\psi\eta(\pi^+\pi^-\pi^0)$ | 1.1            | 2.4                           | 2.2                    | 7.7                             | 8.0                        | ...   | 11.6  |

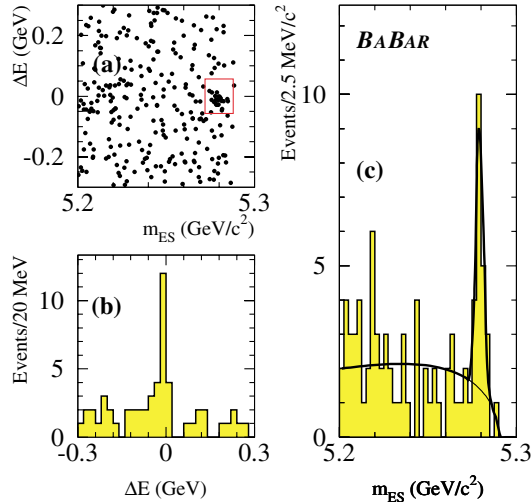


FIG. 2 (color online). The  $B^+ \rightarrow J/\psi\phi K^+$  mode. The  $\Delta E$  vs  $m_{ES}$  event distribution is shown in (a) with a small rectangle corresponding to the signal region selection defined in Table II. The  $\Delta E$  projection with a  $m_{ES}$  signal region selection is shown in (b). The  $m_{ES}$  projection with a  $\Delta E$  signal region selection is shown in (c). The solid line in (c) is the fit described in the text. The Gaussian component includes both the signal and peaking background.

fractional systematic error in Table III. An additional check based on Monte Carlo samples with an intermediate state gives negligible effect.

The total systematic error for each mode combines all these separate errors in quadrature and is listed (Total) in Table III.

There is evidence for signals in the  $J/\psi\phi K^+$  and  $J/\psi\phi K_S^0$  modes. The results are shown in Figs. 2 and 3. The branching fraction for these modes is determined by a simple subtraction of events in the signal region that yields the number of signal events,  $n_s = n_0 - n_b$ . The calculation of the branching fraction is based on the efficiency,  $n_s$ ,  $N_{BB}$ , and the secondary branching fractions [13] for the  $J/\psi$ ,  $\phi$ , and  $K_S^0$ . Table II includes branching fractions, the statistical and systematic errors, the derived result for  $B^0 \rightarrow J/\psi\phi K^0$ , and the probability for a null hypothesis ( $P$  value) which is the Poisson probability that the background fluctuates to  $n_0$  or greater. This probability is calculated using both the central value of our background estimate  $n_b$  and the value increased by 1 standard deviation,  $n_b + \sigma_b$ . This provides an estimate of probability including the background systematic uncertainty.

For modes with no signal or limited statistical evidence ( $J/\psi\phi$ ,  $J/\psi\eta$ ,  $J/\psi\eta'$ ), we determine both a central confidence interval and an upper limit interpretation for the branching fraction. The upper limit method uses  $n_0$ ,  $n_b$ ,  $\sigma_b$ , and the total systematic uncertainty  $\sigma_T$ . Assuming the two uncertainties ( $\sigma_b$ ,  $\sigma_T$ ) are uncorrelated and Gaussian, the Bayesian upper limit on the number of events ( $N_{90\%}$ ) is obtained by folding the Poisson distribution with two normal distributions for these two uncer-

tainties and integrating it to the 90% confidence level (C.L.). This assumes the prior branching fraction distributions are uniform.

In Table II, we list the efficiency, the number of observed events, the expected number of background events, the  $P$  value, the 90% C.L. upper limit for observed events, the corresponding branching fraction limit, and a central interval for the branching fraction. The upper limit obtained from the combination of the two  $B^0 \rightarrow J/\psi\eta$  modes is shown in Table II. We also combine the observed numbers of events for the two  $B^0 \rightarrow J/\psi\eta$  modes to calculate a branching fraction of  $(1.6 \pm 0.6(\text{stat}) \pm 0.1(\text{syst})) \times 10^{-5}$  and the combined probability that the background fluctuates up to the observed number of events or higher is  $(2.6\text{--}33) \times 10^{-5}$ , where the background is estimated using its central value and a value increased by 1 standard deviation.

In summary, we determine the branching fraction of  $B \rightarrow J/\psi\phi K$  in two modes,  $\mathcal{B}(B^+ \rightarrow J/\psi\phi K^+) = (4.4 \pm 1.4 \pm 0.5) \times 10^{-5}$  and  $\mathcal{B}(B^0 \rightarrow J/\psi\phi K_S^0) = (5.1 \pm 1.9 \pm 0.5) \times 10^{-5}$ . The branching fraction of  $B \rightarrow J/\psi\phi K$  is consistent with and much improved over the CLEO [14] result,  $(8.8^{+3.5}_{-3.0} \pm 1.3) \times 10^{-5}$ . Upper limits have been determined for the modes  $B^0 \rightarrow J/\psi\phi$ ,  $J/\psi\eta$ , and  $J/\psi\eta'$ . The  $B^0 \rightarrow J/\psi\eta$  search is significantly more sensitive than the L3 Collaboration [15] results which set a limit of  $<1.2 \times 10^{-3}$  at 90% C.L. In addition, the branching fraction from the combined  $B^0 \rightarrow J/\psi\eta$  modes is comparable to the  $B^0 \rightarrow J/\psi\pi^0$  branching fraction [3]. Finally, the search and resulting branching fraction upper limits for  $B^0 \rightarrow J/\psi\eta'$  and  $B^0 \rightarrow J/\psi\phi$  are presented.

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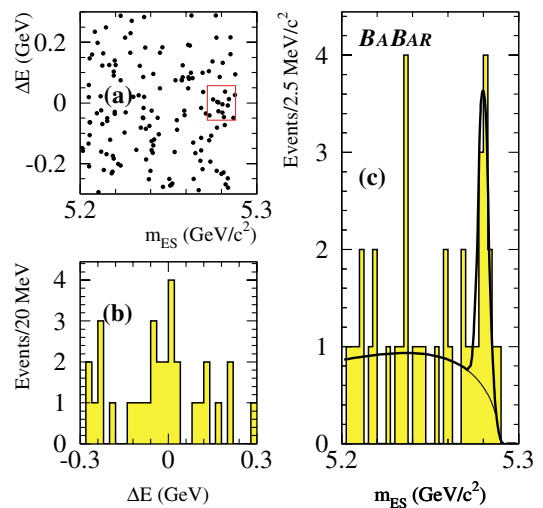


FIG. 3 (color online). The  $B^0 \rightarrow J/\psi\phi K_S^0$  mode. The descriptions of (a), (b), and (c) follow those of Figs. 2(a)–2(c), respectively.

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