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# Evidence for the Rare Decay $B \to \mathbf{J}/\psi\eta\mathbf{K}$

The *BABAR* Collaboration

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## Abstract

We report evidence for the $B$ meson decays, $B^{\pm} \to J/\psi\eta K^{\pm}$ and $B^0 \to J/\psi\eta K^0_S$, using 90 million $B\overline{B}$ events collected at the $\Upsilon(4S)$ resonance with the *BABAR* detector at the PEP-II $e^+e^-$ asymmetric-energy storage ring. We obtain preliminary branching fractions in the charged and neutral channels of $(10.8 \pm 2.3(stat.) \pm 2.4(syst.)) \times 10^{-5}$ and $(8.4 \pm 2.6(stat.) \pm 2.7(syst.)) \times 10^{-5}$, respectively.

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The first observation of color-suppressed B decay modes with hidden strangeness, $s\overline{s}$, was in the decay mode, $B \to J/\psi\phi K$, by the CLEO collaboration [1] and more recently from the BaBar collaboration [2]. The color suppressed B decay modes are represented at the parton level in Figure 1.

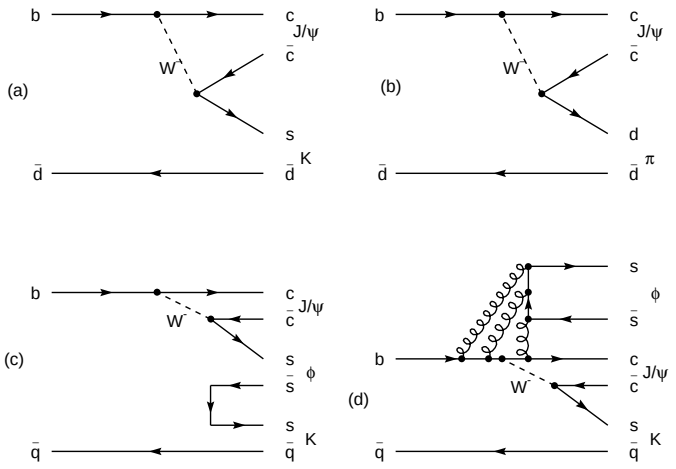


Figure 1: The Feynman diagrams of color-suppressed B decays

Figures 1(a) and (b) show Feynman diagrams for two-body final state color-suppressed B decays into Cabbibo allowed ($J/\psi K$) and Cabbibo suppressed ($J/\psi\pi$) modes. The color suppression is due to the requirement that the color of the quark and anti-quark from the $W$ decay must appropriately be matched with the charm quark and the anti-d quark such that the final state particles are color singlets. Producing a $\phi$ meson in a three-body final state may be achieved by the addition of $s\overline{s}$ quark-antiquark pairs as shown in Figure 1 (c). It is possible also that a $\phi$ is formed from three gluon emission as shown in the OZI violating decay in Figure 1(d). Since the $\eta$ meson is described by the quark-antiquark combination,

$$\eta = \frac{u\overline{u} + d\overline{d} - 2s\overline{s}}{\sqrt{2}}$$

we would also expect B mesons, via the similar diagrams, to decay into states with an $\eta$, such as $B \to J/\psi\eta K$, where the $s\overline{s}$ pairs or two gluons form an $\eta$ instead of a $\phi$. Experimentally, the $\eta$ is seen in charmless decays at a somewhat anomalously high rate [3], which suggests that gluonic $\eta$ couplings are large. This may lead to an enhancement in the decay rate of $B \to J/\psi\eta K$. Since the basic diagrams are the same, we would expect the branching fraction of this mode to be comparable to BR($B \to J/\psi\phi K$)= $(4.4 \pm 1.4 \pm 0.5) \times 10^{-5}$ [2]. If the rate for non-resonant $B \to J/\psi\eta K$ is found to be much higher or lower, then some other physics may be indicated.

If the mode $B \to J/\psi\eta K$ is observed, the neutral mode may be useful for *CP* violation studies [4], [5] and investigation of quasi-two body decays. The decay, $B \to \psi(2s)K$, has been observed, and hence the decay $B \to \psi(2s)K \to J/\psi\eta K$ should be produced where the $J/\psi\eta$ are in a relative P-wave state with an inferred branching fraction [6] of $B(B^+ \to \psi(2s)K^+ \to J/\psi\eta K^+) = (2.1 \pm 0.2) \times 10^{-5}$. If we observe a two body S-wave J/$\psi\eta$ resonance, it would have the quantum

numbers, $J^{PC} = 1^{+-}$, which are those of the unconfirmed $h_c$. However, since the mass threshold of J/$\psi\eta$ is 3.64 GeV/$c^2$, which is higher than the lowest lying $h_c$ mass (estimated as the average of the three $\chi$ state masses), such an observed resonance could indicate a new particle state. We note in addition that if a $J/\psi\eta$ resonance is found with a mass higher than open charm threshold ($\sim$3.77 GeV/$c^2$) it is unlikely to be a conventional charmonium state.

The data used in this analysis correspond to a total integrated luminosity of 81.87 fb$^{-1}$ taken on the $\Upsilon(4S)$ resonance producing a sample of $89.96 \pm 0.99$ million $B\overline{B}$ events ($N_{B\overline{B}}$). The data were collected at the PEP-II asymmetric-energy $e^+e^-$ storage ring with the *BABAR* detector, fully described elsewhere [7]. The *BABAR* detector includes a five-layer silicon vertex tracker (SVT) and a forty-layer drift chamber (DCH) in a 1.5-T solenoidal magnetic field. These devices detect charged particles and measure their momentum and energy loss. Photons and neutral hadrons are detected in a CsI(Tl) crystal electromagnetic calorimeter (EMC). The EMC detects photons with energies as low as 20 MeV and identifies electrons by their energy deposition. An internally reflecting ring-imaging Cherenkov detector (DIRC), composed of quartz bars, measures the charged particle velocity for particle identification. Penetrating muons and neutral hadrons are identified by the steel flux return, which is instrumented with 18-19 layers of resistive plate chambers (IFR).

The preliminary selection criteria in this analysis follow previous *BABAR* analyses [8] and are briefly recalled here. All charged track candidates are required to have at least 12 DCH hits and transverse momentum greater than 100 MeV/$c$. The track candidates not associated with a $K^0_S$ decay must also originate near the nominal beam spot. The muon, electron, and kaon candidates must have a polar angle in radians of $0.3 < \theta_\mu < 2.7$, $0.410 < \theta_e < 2.409$, and $0.45 < \theta_K < 2.50$, respectively. In addition, all charged kaon candidates are required to have a laboratory momentum greater than 250 MeV/$c$. These requirements ensure the selection of tracks in the regions where the acceptance is well understood by the particle identification (PID) systems.

The detailed explanation the PID is given elsewhere [9], [10]. Briefly, photon candidates are identified from energy deposited in contiguous EMC crystals, summed together to form a cluster with total energy greater than 30 MeV and a shower shape consistent with that expected for electromagnetic showers. Electron candidates are required to have a good match between the expected and measured energy loss (d$E$/d$x$) in the SVT and DCH, and between the expected and measured Cherenkov angle in the DIRC. The measurements of the ratio of EMC shower energy to track momentum, and the number of EMC crystals associated with the track candidate must be appropriate for an electron. Muons are selected based on the energy deposited in the EMC, the number and distribution of hits in the IFR, the match between the IFR hits and the extrapolation of the track by the DCH into the IFR, and the depth of penetration of the track into the IFR. Charged kaon candidates are selected based on energy loss information from the SVT and DCH and the Cherenkov angle measured by the DIRC.

The intermediate states in the decay modes used in this analysis, $J/\psi\,(e^+e^-)$, $J/\psi\,(\mu^+\mu^-)$, and $K^0_S\,(\pi^+\pi^-)$, are selected within the mass intervals listed in Table 1. The di-electron mass interval is larger than the di-muon to account for Bremstrahlung in the detector. The $K^0_S$ decay length is required to be greater than 0.1 cm.

The remaining four selection criteria are the $\eta$ mass, the $\pi^0$ veto, the photon helicity angle [8] from the $\eta$ decay and the thrust angle. In the following we describe each of these criteria and the process used to determine their final cut values.

The $\eta$ candidates are required to have $\gamma\gamma$ mass within the range listed in Table 1. If either of the photons associated with an $\eta$ candidate, in combination with any other photon in the event, forms a $\gamma\gamma$ mass near the nominal $\pi^0$ mass, the $\eta$ candidate is vetoed as a $\pi^0$ background. The

$\pi^0$ veto selection was adjusted by limiting the mass difference between all possible $\gamma\gamma$ masses and the nominal $\pi^0$ mass as shown Table 1. The $\eta$ candidate is rejected if $\left|\cos\theta_\gamma^\eta\right|$ is near 1, where $\theta_\gamma^\eta$ 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 distribution that peaks at 0 or 180 degrees.

An additional requirement is applied to separate two-jet continuum events from the more spherical $B$ meson decays. The angle $\theta_T$ between the thrust [8] direction of the $B$ meson candidate and the thrust direction of the remaining tracks in the event is calculated. We reject events when $|\cos\theta_T|$ is near 1, since the distribution in $\cos\theta_T$ is flat for $B\overline{B}$ events, while for background continuum events the distribution is peaked at $\cos\theta_T = \pm 1$.

Estimation of the signal and the background use two kinematic variables: the energy difference $\Delta E$ between the energy of the $B$ candidate and the beam energy $E_b^*$ in the $\Upsilon(4S)$ rest frame; and the energy-substituted mass $m_{\rm ES} = \sqrt{(E_b^*)^2 - (P_B^*)^2}$, where $P_B^*$ is the reconstructed momentum of the $B$ candidate in the $\Upsilon(4S)$ frame. Typically these two variables in a two-dimensional plot for the $B$ meson signal will appear as a weakly correlated two-dimensional Gaussian distribution, whereas the background is roughly uniformly distributed. The $\Delta E$ and $m_{ES}$ resolutions are mode dependent. A signal region for each mode, $B^+$ and $B^0$, is defined as a rectangular region in the $\Delta E$ versus $m_{\rm ES}$ plane with $|m_{\rm ES} - m_B| < 7.5$ MeV/c$^2$, where $m_B$ is the mass of $B$ meson and $|\Delta E|$ <40 MeV. Before the data were analyzed, these four final selection criteria were optimized using a Monte Carlo (MC) simulation of the signal and the known backgrounds. Motivated by the $B \to J/\psi\phi K$ measurement, the *ab initio* value of the branching fraction for $B \to J/\psi\eta K$ used in the signal MC was $5 \times 10^{-5}$. The number of reconstructed MC signal events ($n_s^{mc}$) and the number of reconstructed MC background events ($n_b^{mc}$) in the signal box were obtained using the same criteria to estimate the signal significance ratio, $n_s^{mc}/\sqrt{n_s^{mc} + n_b^{mc}}$. This ratio was maximized by varying these four selection criteria. The resulting criteria were fixed and are listed in Table 2. The resulting $\Delta E$ and $m_{\rm ES}$ distributions for data are shown in Figs. 2 and 3. The number of data events ($n_0$) observed in the signal box region for each mode, $B^+$ and $B^0$, is listed in Table 3.

The $m_{\rm ES}$ distribution background shape is determined by fitting the line shape of an ARGUS function [8] for each mode to the $m_{\rm ES}$ distributions formed from the $\Delta E$ sideband region of the on-peak data of $0.1 < |\Delta E| < 0.14$ for the $B^+$ mode and $0.08 < |\Delta E| < 0.28$ for the $B^0$ mode. To determine the number of signal events, we fit the data $m_{\rm ES}$ distribution to a model ( see Figs. 2(c) and 3(c) ) that is the sum of this ARGUS function whose normalization is allowed to vary, and a signal Gaussian, whose width is fixed to the MC value but whose mean and normalization are allowed to vary. The integral of this resulting ARGUS function over the signal box region yields the number of background events ($n_b$) and its uncertainty ($\sigma_b$). Similar $m_{\rm ES}$ background shapes were found by using a $\gamma\gamma$ mass sideband outside the nominal $\eta$ mass. Occasionally backgrounds with an inclusive $J/\psi$ decay will lead to a peaking background near or at the $B$ mass in the $m_{ES}$ distribution. Background shapes consisting of a sum of the ARGUS function and a broad Gaussian were attempted, however its contribution was found to be small and was dropped from the final background fit. The final values of $n_b$ and $\sigma_b$ are listed in Table 3.

We find evidence for signals in the $J/\psi\eta K^+$ and $J/\psi\eta K_S^0$ modes as seen in Figs. 2 and 3. To determine the branching fraction for these modes the number of signal events ($n_s$) is given by a simple subtraction of the estimated number of background events from the events in the signal box region, $n_s = n_0 - n_b$. The efficiencies ($\epsilon$) for each mode, listed in Table 3, are determined by MC simulation with three–body phase space and unpolarized $J/\psi$ decays. The calculation of the

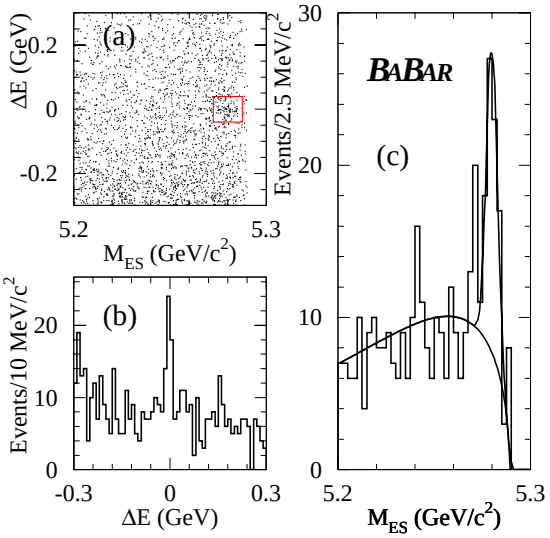


Figure 2: The $\Delta E$ and $m_{\rm ES}$ distributions for $B^+ \to J/\psi\eta K^+$. The $\Delta E$ vs. $m_{\rm ES}$ event distribution is shown in (a) with a small rectangle corresponding to the signal region selection defined in the text. The $\Delta E$ projection within a $m_{\rm ES}$ signal region selection is shown in (b). The $m_{\rm ES}$ projection within a $\Delta E$ signal region selection is shown in (c). The solid line in (c) is the fit described in the text.

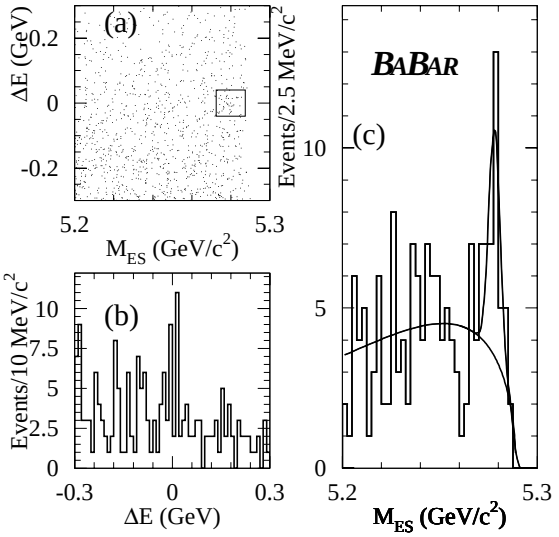


Figure 3: The $\Delta E$ and $m_{\rm ES}$ distributions for $B^0 \to J/\psi\eta K^0_S$. The descriptions of Figs. 3(a), (b) and (c) follow those of Figs. 2(a), (b) and (c), respectively.

branching fraction ($BF$) is

$$BF \;=\; \frac{n_{\rm S}}{N_{B\overline{B}} \times \epsilon \times f}$$

where $\epsilon$ is the efficiency for the mode and $f$ is the product of secondary branching fractions for the $J/\psi$, $\eta$, and $K^0_S$. The results are given in the last column of Table 3 where the first and second $BF$ uncertainities are the statistical and systematic, respectively. The statistical uncertainty is derived from the error on $n_s$ which is $\sqrt{n_0 + \sigma_b^2}$.

In Table 4, we list the contribution to the systematic uncertainty from the error on each of the following quantities: $N_{B\overline{B}}$; secondary branching fractions [6]; MC statistics; PID, tracking, and photon detection efficiencies; $\pi^0$ veto; $\eta$ mass range; background parameterization; and model dependence. The PID, tracking, and photon detection efficiency uncertainties are based on the study of data control samples [11]. The error in the $\pi^0$ veto efficiency was studied by measuring the inclusive $\eta$ rate in both data and MC. After varying the $\pi^0$ veto mass cut, the change in the number of inclusive $\eta$'s was determined in data and MC to measure the deviation between the data and the simulation and to estimate the resulting systematic uncertainty. The uncertainty in the $\eta$ mass range was determined by comparing the measured $\eta$ mass resolution in inclusive $\eta$ decays to the $\eta$ mass resolution from the signal MC. The background parameterization uncertainty was estimated by changing the ARGUS shape parameter by $\pm 1$ standard deviation, refitting the $m_{\rm ES}$ data distribution and recalculating the number of signal events. Additional systematic uncertainties due to the decay model dependence are estimated for the modes $J/\psi\eta K^+$ and $J/\psi\eta K^0_S$. MC simulations are used to determine how much the efficiency depends on assumptions about intermediate resonances and angular distributions. Five samples were studied. One sample is generated with 100% transversely polarized $J/\psi$ and another with 100% longitudinally polarized $J/\psi$. The other three samples had large $J/\psi\eta$ mass, large $\eta K$ mass or small $J/\psi K$ mass. The resulting relative change in efficiency is entered as a fractional systematic uncertainty in Table 4. The total systematic uncertainty for each mode combines all these separate errors in quadrature, is listed the last column in Table 4. and is used to determine the $BF$ systematic uncertainties listed in Table 3.

The probability for a null hypothesis (P-value) is defined as the Poisson probability that the estimated number of background events fluctuates to observed number of events $n_0$ or greater. In Table 3 we provide P-values calculated using the central value of the background estimate $n_b$ and the value increased by 1 standard deviation, $n_b + \sigma_b$, to provide an estimate of probability including the background systematic uncertainty.

We determine also the 90% confidence level upper limit on the branching fraction using $n_0$, $n_b$, and $\sigma_b$, in the signal region, 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 describing these two uncertainties and integrating the resulting function to the 90% confidence level (C.L.). This assumes that the *a priori* branching fraction distributions are uniform. The results are listed in Table 3.

Our preliminary branching fraction is comparable to $B \to J/\psi\phi K$ and is consistent with simple expectations from color-suppressed decay diagrams. The ratio of the charged ($J/\psi\eta K^\pm$) to neutral ($J/\psi\eta K^0_S$) branching fractions is expected to be two which is not inconsistent with our results. Although the current statistics are too small, a larger data set of the neutral mode could be useful for a test of $CP$ violation and both charged and neutral modes may enable a search for resonances in the two body intermediate states.

In summary, we find evidence for the decay $B \to J/\psi\eta K$ in two modes with preliminary branching fractions of, $\mathcal{B}(B^+ \to J/\psi\eta K^+) = (10.8 \pm 2.3 \pm 2.4) \times 10^{-5}$ and $\mathcal{B}(B^0 \to J/\psi\eta K^0_S) = (8.4 \pm 2.6 \pm 2.7) \times 10^{-5}$.

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[8] *BABAR* Collaboration, B. Aubert *et al.*, Phys. Rev. **D65**, 32001 (2002). This publication forms a basic reference of our analysis. The helicity angles and thrust variable are described in section VIIC.1, the ARGUS function and beam energy substituted mass in section VIIC, and the particle identification and tracking criteria for the photons, electrons and muons in sections IIC and IID.

[9] The particle identification selection is taken from ref. [8]. The photon candidates selection is the same as that in ref. [8]. The electron candidates are required to satisfy the "Tight" selections and the muon candidates use the "Loose" selections, as specified in ref. [8].

[10] *BABAR* Collaboration, B. Aubert *et al.*, Phys. Rev. **D66**, 32003, (2002). The charged kaon candidate used a selection slightly more stringent than those described in this reference.

[11] The estimate of the uncertainty on the PID, tracking and photon detection efficiency using control samples from data is described in section XI of ref. [8].

# TABLES

Table 1: Mass regions for selection of intermediate particles.

| Mode | Mass Range (GeV/$c^2$) | | | | |
|---|---|---|---|---|---|
| $J/\psi \to e^+e^-$ | 2.95 | $<$ | $M(e^+e^-)$ | $<$ | 3.14 |
| $J/\psi \to \mu^+\mu^-$ | 3.06 | $<$ | $M(\mu^+\mu^-)$ | $<$ | 3.14 |
| $K^0_S \to \pi^+\pi^-$ | 0.489 | $<$ | $M(\pi^+\pi^-)$ | $<$ | 0.507 |
| $\eta \to \gamma\gamma$ | 0.525 | $<$ | $M(\gamma\gamma)$ | $<$ | 0.571 |

Table 2: Final selection criteria for the $B^{\pm} \to J/\psi\eta(\gamma\gamma)K^{\pm}$ and $B^0 \to J/\psi\eta(\gamma\gamma)K^0_S$ modes.

| Variable | $J/\psi\eta K^+$ | $J/\psi\eta K^0_S$ |
|---|---|---|
| $\lvert M_\eta - 0.547\rvert \leq$ | 0.023 GeV/$c^2$ | 0.023 GeV/$c^2$ |
| $\pi^0$ veto if $\lvert M(\gamma_\eta + \gamma_{other}) - 0.135\rvert \leq$ | 0.017 GeV/$c^2$ | 0.010 GeV/$c^2$ |
| Helicity: $\lvert cos(\theta^\eta_\gamma)\rvert \leq$ | 0.93 | 0.81 |
| Thrust: $\lvert cos(\theta_T)\rvert \leq$ | 0.8 | 0.9 |

Table 3: Branching fractions and 90% C.L. upper limits.

| Mode | $\epsilon$ | $n_0$ | $n_b \pm \sigma_b$ | $N_{90\%}$ | 90% C.L.U.L. ($10^{-5}$) | P-value range | Branching Fraction ($10^{-5}$) |
|---|---|---|---|---|---|---|---|
| $J/\psi\eta K^+$ | 10.75% | 99 | $50.3 \pm 3.0$ | 70.0 | $<$15.5 | $(0.09 - 1.42) \times 10^{-8}$ | $10.81 \pm 2.31 \pm 2.37$ |
| $J/\psi\eta K^0_S$ | 8.53% | 39 | $18.5 \pm 1.7$ | 34.5 | $<$14.1 | $(.23 - 1.3) \times 10^{-4}$ | $8.35 \pm 2.64 \pm 2.67$ |

Table 4: Systematic uncertainty summary on the branching fractions. All are fractional uncertainties in percent.

| Mode | $N_{B\overline{B}}$ | Secondary Branching Fraction | M.C. Stat. | PID, tracking, $\gamma$ Det. | $\pi^0$ veto | $\eta$ mass cut | Bkgd. Param. | Model | Total |
|---|---|---|---|---|---|---|---|---|---|
| $J/\psi\eta K^+$ | 1.1 | 2.48 | 1.77 | 8.2 | 8.1 | 3.40 | 16.7 | 5.1 | 22.0 |
| $J/\psi\eta K^0_S$ | 1.1 | 2.52 | 2.17 | 8.3 | 8.3 | 3.14 | 27.0 | 9.5 | 32.0 |