Observation of the Decay $B \to J/\psi \eta K$ and Search for $X(3872) \to J/\psi \eta$

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We report the observation of the B meson decay $B^{\pm} \to J/\psi \eta K^{\pm}$ and evidence for the decay $B^0 \to J/\psi \eta K^0_S$, using 90×10^6 $B\overline{B}$ events collected at the $\Upsilon(4S)$ resonance with the BABAR detector at the SLAC PEP-II e^+e^- asymmetric-energy storage ring. We obtain branching fractions of $\mathcal{B}(B^{\pm} \to J/\psi \eta K^{\pm}) = [10.8 \pm 2.3(\text{stat}) \pm 2.4(\text{syst})] \times 10^{-5}$ and $\mathcal{B}(B^0 \to J/\psi \eta K^0_S) = [8.4 \pm 2.6(\text{stat}) \pm$

2.7(syst)] $\times 10^{-5}$. We search for the new narrow mass state, the $X(3872)$, recently reported by the Belle Collaboration, in the decay $B^{\pm} \to X(3872)K^{\pm}$, $X(3872) \to J/\psi\eta$ and determine an upper limit of $\mathcal{B}[B^{\pm} \to X(3872)K^{\pm} \to J/\psi\eta K^{\pm}] < 7.7 \times 10^{-6}$ at 90% confidence level.

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The study of charmonium production in exclusive B meson decays led to the discoveries of new states. Since B mesons can decay via color-suppressed $b \to c\bar{c}s$ quark transitions, the charmonium states are typically produced in final states with kaons. Many known charmonium states have been observed in decays such as $B \to J/\psi K^{(*)}$, $\psi(2S)K^{(*)}$, $\chi_c K^{(*)}$, and $\eta_c(1S)K^{(*)}$, and evidence for new states such as a candidate for the $\eta_c(3654)$ has been published [1]. Recently the Belle Collaboration [2] observed a new narrow mass state with a 3.872 GeV$/c^2$ mass produced in the decay $B^{\pm} \to X(3872)K^{\pm}$, $X(3872) \to \pi^+\pi^- J/\psi$. This new state may be the hitherto undetected $J^{PC} = 2^{--}$ 1^3D_2 charmonium state [3]. However, such a state should have a large radiative $E1$ dipole transition into $\gamma\chi_{c1}$, which Belle does not observe, and theoretical models [3] predict a smaller mass splitting, relative to the $\psi(3770)$, than observed. Unconventional explanations include a molecule [4] formed with charmed D and D^* mesons, since the $X(3872)$ has a mass exactly at $D^{*0}(2007) + D^0(1864)$ threshold. Alternatively, this new state may be a hybrid charmonium state [5] formed of $c\bar{c}$ + gluons since color octet charmonium states may be produced in exclusive B decays [6].

To further elucidate the nature of the $X(3872)$, we analyze the exclusive decay $B \to J/\psi\eta K$ and search for $X(3872) \to J/\psi\eta$. If the $X(3872)$ is a conventional charmonium state, its decays may be similar to the $\psi(2S)$, which decays into $J/\psi\pi^+\pi^-$ and, with a factor of 10 smaller relative rate, into $J/\psi\eta$. If instead, it is a hybrid charmonium state, it is also predicted [5] to decay into $J/\psi\pi\pi$ and $J/\psi\eta$. The latter mode may have an enhanced rate [7] if there are gluonic couplings in the η.

The decay $B \to J/\psi\eta K$ is similar at the quark level to other color-suppressed decays such as $B \to J/\psi\phi K$, which has been observed with a branching fraction of $(4.4 \pm 1.4 \pm 0.5) \times 10^{-5}$ [8]. Hence it might be expected that $B \to J/\psi\eta K$ has a comparable branching fraction.

The data used in this analysis correspond to a total integrated luminosity of 81.9 fb^{-1} taken on the $\Upsilon(4S)$ resonance, producing a sample of $90.0 \pm 1.0 \times 10^6$ $B\bar{B}$ events ($N_{B\bar{B}}$). Data were collected at the SLAC PEP-II asymmetric-energy e^+e^- storage ring with the BABAR detector, fully described elsewhere [9]. The BABAR detector includes a silicon vertex tracker and a drift chamber in a 1.5-T solenoidal magnetic field to detect charged particles and measure their momenta and energy loss. Photons, electrons, and neutral hadrons are detected in a CsI(Tl)-crystal electromagnetic calorimeter. An internally reflecting ring-imaging Cherenkov detector is used for particle identification. Penetrating muons and neutral hadrons are identified by resistive-plate chambers in the steel flux return. Preliminary track-selection criteria in this analysis follow previous BABAR analyses [10] and the detailed explanation of the particle identification (PID) is given elsewhere [10,11].

The intermediate states in the charged ($J/\psi\eta K^{\pm}$) and neutral ($J/\psi\eta K^0_S$) modes used in this analysis, $J/\psi \to e^+e^-$, $J/\psi \to \mu^+\mu^-$, $\eta \to \gamma\gamma$, and $K^0_S \to \pi^+\pi^-$, are selected within the mass intervals $2.95 < M(e^+e^-) < 3.14$, $3.06 < M(\mu^+\mu^-) < 3.14$, $0.525 < M(\gamma\gamma) < 0.571$, and $0.489 < M(\pi^+\pi^-) < 0.507$ GeV$/c^2$. The mass interval for e^+e^- is larger than for $\mu^+\mu^-$ to enable detection of events with bremsstrahlung in the detector. The K^0_S decay length in the lab frame is required to be greater than 0.1 cm.

The analysis utilizes two kinematic variables [8]: the energy difference ΔE between the energy of the B candidate and the beam energy E^*_b in the $\Upsilon(4S)$ rest frame; and the beam-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 $\Upsilon(4S)$ frame. Signal events concentrate in a rectangular signal-box region bounded by $|m_{ES} - m_B| < 7.5$ MeV$/c^2$, where m_B is the mass of B meson and $|\Delta E| < 40$ MeV.

Before the data were analyzed, the final selection criteria were optimized separately for each mode using a Monte Carlo (MC) simulation of both the signal and backgrounds. Motivated by the $B \to J/\psi\phi K$ measurement, the MC signal branching fraction for $B \to J/\psi\eta K$ was set to 5×10^{-5}. The number of reconstructed MC signal events n^{mc}_s and the number of reconstructed MC background events n^{mc}_b in the signal box were used to estimate the sensitivity ratio, $n^{mc}_s/\sqrt{n^{mc}_s + n^{mc}_b}$. This ratio was maximized by varying the selection criteria on the η mass, a π^0 veto, the photon helicity angle from the η decay, and the thrust angle. The $\gamma\gamma$ mass interval of the η candidate as specified earlier was chosen by this procedure. In the charged (neutral) mode, if either of the photons associated with an η candidate, in combination with any other photon in the event, forms a $\gamma\gamma$ mass within 17(10) MeV$/c^2$ of the nominal π^0 mass, the η candidate is vetoed as a π^0 background. The η candidate is rejected if $|\cos\theta^{\eta}_{\gamma}|$ is greater than 0.93(0.81), where θ^{η}_{γ} is the photon helicity angle [10] in the η rest frame. Signal events have a uniform $\cos\theta^{\eta}_{\gamma}$ distribution, whereas combinatorial background of random pairs of photons typically has a distribution that peaks near ± 1.

To separate two-jet continuum events from the more spherical decays of B mesons produced nearly at rest from

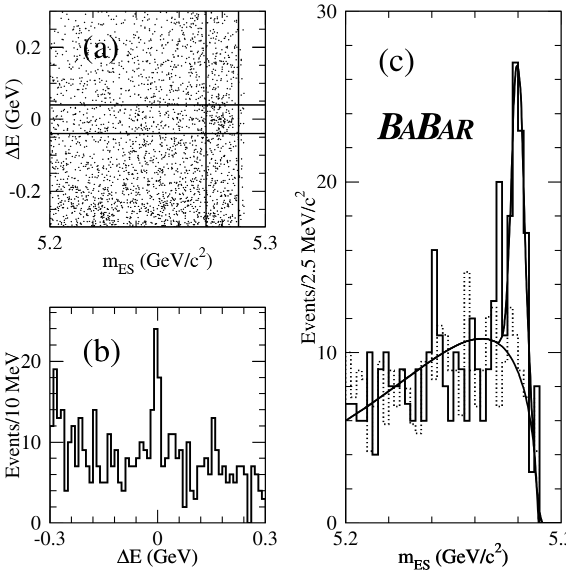

FIG. 1. For $B^{\pm} \to J/\psi \eta K^{\pm}$, the ΔE versus m_{ES} event distribution (a) is shown with vertical and horizontal bands defined by limits, $|m_{\mathrm{ES}} - m_{\mathrm{B}}| < 7.5\ \mathrm{MeV}/c^2$ and $|\Delta E| < 40$ MeV, respectively. The intersection of these bands corresponds to the signal-box region defined in the text. The ΔE projection (b) is shown for events in the vertical band that contains the m_{ES} signal region. The m_{ES} projection (c) is shown for events in the horizontal band that contains the ΔE signal region. The dashed histogram represents the estimated background and is described in the text.

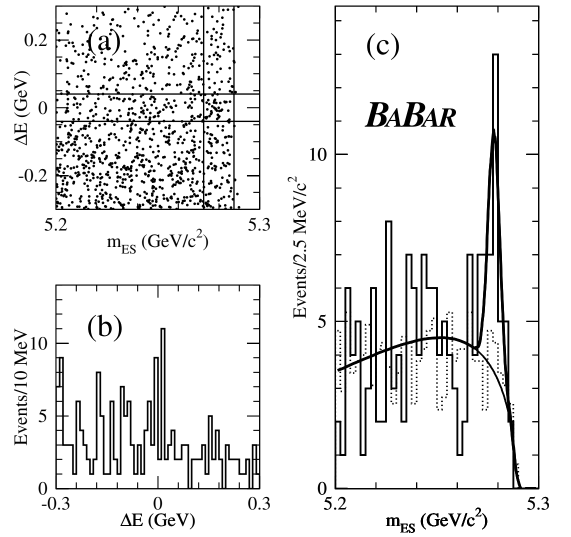

FIG. 2. The ΔE and m_{ES} distributions for $B^0 \to J/\psi \eta K^0_S$. The descriptions of (a), (b), and (c) follow those of Figs. 1(a), 1(b), and 1(c), respectively.

$\Upsilon(4S) \to B\overline{B}$, the angle θ_{T} between the thrust [10] direction of the B meson candidate and the thrust direction of the remaining charged tracks and photons in the event is calculated. We reject charged (neutral) mode events when $|\cos\theta_{\mathrm{T}}|$ is greater than 0.8 (0.9), since the distribution in $\cos\theta_{\mathrm{T}}$ is flat for $B\overline{B}$ events, while background $e^+e^- \to q\overline{q}$ continuum events peak at $\cos\theta_{\mathrm{T}} = \pm 1$.

The data, after these cuts, are shown in Figs. 1 and 2 and where (a) is a scatter plot of ΔE versus m_{ES}, (b) is the ΔE histogram, and (c) is the m_{ES} histogram (solid line). There are signal peaks in the m_{ES} and ΔE distributions for both modes. If we exclude events with $\eta \to \gamma\gamma$ by changing the $0.525 < M(\gamma\gamma) < 0.571$ selection to $0.470 < M(\gamma\gamma) < 0.493$ or $0.597 < M(\gamma\gamma) < 0.620$, the signal peaks disappear in both modes. Hence we find evidence for B signals in both the $J/\psi \eta K^{\pm}$ and $J/\psi \eta K^0_S$ modes.

To determine the branching fraction for these modes, we first find the number of signal events, which is defined as $n_{\mathrm{s}} = n_0 - n_{\mathrm{b}}$, where n_0 is the number of events in the signal-box region, and n_{b} is the estimated number of background events. For each mode, n_{b} is obtained from fitting the m_{ES} distribution for events with $|\Delta E| <$ 40 MeV with the line shape of a Gaussian function and an ARGUS function [10], which is an empirical parametrization of the background shape. The fit parameters are the normalization and mean of the Gaussian and the normalization of the background curve. The width of the Gaussian is fixed to the value determined by MC simulation and the shape of the background curve is fixed to a best fit to the data m_{ES} distribution with the ΔE sideband region of $0.10 < |\Delta E| < 0.14$ GeV for the $B^{\pm}$ mode and $0.08 < |\Delta E| < 0.28$ GeV for the B^0 mode. Figures 1(c) and 2(c) show the resulting Gaussian and background curves (solid line) and the background events (dashed histogram) from the ΔE sideband regions normalized to the data in the signal region. Integrating the background curve over the signal-box region we obtain n_{b} and its uncertainty, σ_{b}. Results are listed in Table I.

The branching fraction is calculated as $\mathcal{B} = n_{\mathrm{s}}/(N_{B\overline{B}} \times \epsilon \times f)$, where ϵ is the efficiency and f is the product of secondary branching fractions for the J/ψ, η, and K^0_S. Efficiencies are determined by the MC

TABLE I. Efficiencies, number of signal-box and background events, 90% C.L. of the number of events and the branching fraction upper limits, P-values and branching fractions.

Mode	ϵ	n_0	$n_{\mathrm{b}} \pm \sigma_{\mathrm{b}}$	$N_{90\%}$	90% C.L.U.L.	P value	Branching fraction
$J/\psi \eta K^{\pm}$	10.75%	99	50.3 ± 3.0	70.0	$<15.5 \times 10^{-5}$	2×10^{-8}	$(10.8 \pm 2.3 \pm 2.4) \times 10^{-5}$
$J/\psi \eta K^0_S$	8.53%	39	18.5 ± 1.7	34.5	$<14.1 \times 10^{-5}$	9×10^{-5}	$(8.4 \pm 2.6 \pm 2.7) \times 10^{-5}$

simulation with three-body phase space and the branching fractions of $\Upsilon(4S) \to B^+B^-$ and $\Upsilon(4S) \to B^0\overline{B}^0$ are assumed to be equal. Results on $\mathcal{B}$ are given in the last column of Table I where the first and second errors are statistical and systematic, respectively. The statistical error is derived from the uncertainty in n_s which is $\sqrt{n_0 + \sigma_b^2}$.

The systematic error, σ_{sys}, for each mode (charged/neutral) is determined by adding in quadrature the percentage uncertainty on each of the following quantities: $N_{B\overline{B}}$ (1.1%/1.1%); secondary branching fractions [12] (2.48%/2.52%); MC statistics (1.77%/2.17%); PID, tracking, and photon detection efficiencies (8.2%/8.3%); π^0 veto (8.1%/8.3%); η mass range (3.40%/3.14%); background parametrization (16.7%/27.0%); and model dependence (5.1%/9.5%). The total systematic errors for the charged and neutral modes are 22.0% and 32.0%, respectively. The uncertainties in the PID, tracking, and photon detection efficiencies are based on the study of data control samples [10]. The uncertainty in the π^0 veto efficiency was studied by measuring the veto efficiency on the inclusive η rate in data and in the MC calculation. The uncertainty due to the η mass selection was determined by comparing the measured η mass resolution in inclusive η decays to the η mass resolution from the signal MC calculation. The background parametrization uncertainty was estimated by changing the ARGUS shape parameter by ± 1 standard deviation, refitting the m_{ES} data distribution, and recalculating the number of signal events. Although this analysis used MC events generated with three-body phase space to determine the final efficiencies, additional systematic uncertainties due to the decay model dependence are estimated. The efficiency uncertainty due to unknown angular distributions and intermediate resonances has been estimated by comparing the efficiencies obtained in five different MC generated models. These include 100% transversely polarized J/ψ, 100% longitudinally polarized J/ψ, large two-body $J/\psi\eta$ mass, large two-body ηK mass, and small two-body $J/\psi K$ mass. The resulting relative change in efficiencies was used to estimate the production model uncertainty. The resulting total σ_{sys} for each mode is used to determine the $\mathcal{B}$ systematic errors in Table I.

The P value for null hypothesis (no signal) is the Poisson probability that the background events fluctuate to $\geq n_0$. Assuming the probability distribution function of the background is a Gaussian with mean n_b and standard deviation σ_b, we calculate the Poisson probabilities with different background values weighted by this Gaussian distribution to determine the final P value for each mode. The resulting P values are equivalent to a statistical significance of 5.6σ and 3.9σ for the charged and neutral modes, respectively. If we remove the direct decays, $B^\pm \to \psi(2S)K^\pm$, $\psi(2S) \to J/\psi\eta$, from our sample by selecting events with $M(J/\psi\eta) > 3.75$ GeV$/c^2$ and apply the same signal/background extraction procedure, we obtain P values of 2.0×10^{-6} and 5.6×10^{-5} for the charged and neutral modes, respectively.

We also determine the 90% confidence level upper limit (C.L.U.L.) on the branching fraction using n_0, n_b, and σ_b, in the signal region, and σ_{sys}. The Bayesian upper limit on the number of signal events, $N_{90\%}$, is obtained by folding the Poisson distribution with two Gaussian distributions representing the background and systematic uncertainties and integrating the resulting function to the 90% confidence level (C.L.). This assumes that the *a priori* branching fraction distributions are flat. The charged and neutral results, $J/\psi\eta K^\pm$ and $J/\psi\eta K_S^0$, are listed in Table I.

Our resulting branching fractions are comparable to the color-suppressed decay $B \to J/\psi\phi K$ branching fraction. The ratio of the charged to neutral branching fractions is consistent within errors to the expected value of 2.

We search for the $X(3872)$ in $B \to XK, X \to J/\psi\eta$ selecting the signal region, $|m_{ES} - m_B| < 7.5$ MeV$/c^2$ and $|\Delta E| < 40$ MeV. The resulting $J/\psi\eta$ mass distribution is shown in Fig. 3. The two-body mass resolution from Monte Carlo studies is 6 MeV$/c^2$. There is possible evidence for the $\psi(2S)$ and no evidence for the $X(3872)$. Using the measured branching fractions $\mathcal{B}(B^\pm \to \psi(2S)K^\pm, \psi(2S) \to J/\psi\eta) = (2.16 \pm 0.19) \times 10^{-5}$ [12], we expect to reconstruct 12 ± 1 events in the charged mode in the $J/\psi\eta$ mass region below 3.710 GeV$/c^2$ and we observe 15. After restricting the mass to $3.85 < M(J/\psi\eta) < 3.89$ GeV$/c^2$, we fit the m_{ES} plot with the same procedure as before and obtain an upper limit for the product branching fraction $\mathcal{B}(B^\pm \to X(3872)K^\pm, X \to J/\psi\eta) < 7.7 \times 10^{-6}$ at 90% C.L.

Our resulting upper limit may be compared to the Belle result [2], $\mathcal{B}(B^\pm \to X(3872)K^\pm \to J/\psi\pi^+\pi^-K^\pm)/\mathcal{B}(B^\pm \to \psi(2S)K^\pm \to J/\psi\pi^+\pi^-K^\pm) = (6.3 \pm 1.2 \pm 0.7)\%$. Using $\mathcal{B}(B^\pm \to \psi(2S)K^\pm \to J/\psi\pi^+\pi^-K^\pm) = (2.0 \pm 0.15 \pm 0.22) \times 10^{-4}$ [12] it can be deduced that $\mathcal{B}(B^\pm \to X(3872)K^\pm \to J/\psi\pi^+\pi^-K^\pm) = (12.6 \pm 2.8 \pm 1.2) \times 10^{-6}$. If the matrix elements for $X(3872) \to J/\psi\pi^+\pi^-$ and $J/\psi\eta$ are similar to those of the $\psi(2S)$ and we include the larger phase space for the decay of

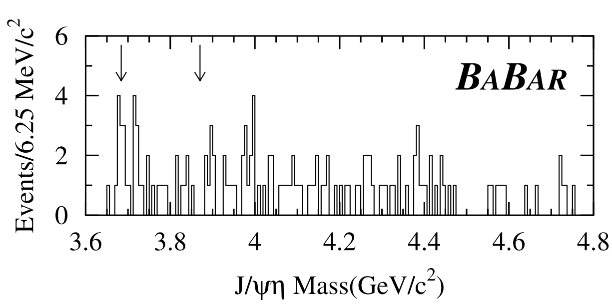

FIG. 3. The summed $J/\psi\eta$ mass distributions from $B^\pm \to J/\psi\eta K^\pm$ and $B^0 \to J/\psi\eta K_S^0$. The arrows indicate where the $\psi(2S)$ and $X(3872)$ signals would appear.

$X(3872) \to J/\psi\eta$ relative to the $\psi(2S)$, then we would expect $\mathcal{B}(B^{\pm} \to X(3872)K^{\pm} \to J/\psi\eta K^{\pm}) \sim 3 \times 10^{-6}$. Our upper limit is within a factor of 2 of this estimate. This result is consistent with the charmonium interpretation of the $X(3872)$ and restricts the magnitude of possible enhancements with hybrid states.

In conclusion, we have made the first observation of the decay mode $B \to J/\psi\eta K$ with branching fractions of $\mathcal{B}(B^{\pm} \to J/\psi\eta K^{\pm}) = (10.8 \pm 2.3 \pm 2.4) \times 10^{-5}$ and $\mathcal{B}(B^{0} \to J/\psi\eta K^{0}_{S}) = (8.4 \pm 2.6 \pm 2.7) \times 10^{-5}$. We set an upper limit for the $X(3872)$ in the product branching fraction, $\mathcal{B}(B^{\pm} \to X(3872)K^{\pm} \to J/\psi\eta K^{\pm}) < 7.7 \times 10^{-6}$ at 90% C.L.

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