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Observation of the exclusive reaction $e^+e^- \to \phi\eta$ at $\sqrt{s} = 10.58$ GeV

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We report the observation of $e^+e^- \to \phi\eta$ near $\sqrt{s} = 10.58$ GeV with 6.5σ significance in the $K^+K^-\gamma\gamma$ final state in a data sample of 224 fb^{-1} collected by the *BABAR* experiment at the PEP-II e^+e^- storage rings. We measure the restricted radiation-corrected cross section to be $\sigma(e^+e^- \to \phi\eta) = 2.1 \pm 0.4(\text{stat}) \pm 0.1(\text{syst})$ fb within the range $|\cos\theta^*| < 0.8$, where θ^* is the center-of-mass polar angle of the ϕ meson. The ϕ meson is required to be in the invariant mass range of $1.008 < m_\phi < 1.035$ GeV/c^2. The radiation-corrected cross section in the full $\cos\theta^*$ range is extrapolated to be $2.9 \pm 0.5(\text{stat}) \pm 0.1(\text{syst})$ fb.

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The large data samples of the B factories provide an opportunity to explore rare exclusive quasi-two-body processes in e^+e^- annihilation, such as final states produced through one virtual photon with negative C-parity ($J/\psi\eta_c$ or other double charmonium states) [1,2], and two-virtual-photon annihilation (TVPA) with positive C-parity ($\rho^0\rho^0$ or $\phi\rho^0$) [3]. The process $e^+e^- \to J/\psi\eta_c$ and other double charmonium processes are observed at rates approximately 10 times larger than the expectation from QCD-based models [4]. Various theoretical efforts have been made to resolve the discrepancy between experimental and theoretical results [5–7]. Another avenue to explore this puzzle is provided by the related process $e^+e^- \to \phi\eta$. A recent observation of $\psi(3770) \to \phi\eta$ at a branching fraction of $(3.1 \pm 0.6 \pm 0.3 \pm 0.1) \times 10^{-4}$ [8] also stimulates a search for $\Upsilon(4S) \to \phi\eta$.

We report the observation of $e^+e^- \to \phi\eta$, which is analogous, in the s quark sector, to the process $e^+e^- \to J/\psi\eta_c$, since the η meson has an $s\bar{s}$ quark-pair component. The Feynman diagram for the most likely production mechanism is shown in Fig. 1. However, since η is not purely $s\bar{s}$, the cross section for this production mechanism is determined by the projection onto the $s\bar{s}$ component of the η meson. A calculation using the QCD-based light cone method with relativistic treatment for the light s quark is possible and therefore can provide a theoretical estimation [9].

The $\phi\eta$ combination is a vector-pseudoscalar (VP) final state. The production rates for $e^+e^- \to$ VP can be described by form factors, which are predicted in QCD-based models [10–12]. Different models predict different dependences on center-of-mass (CM) energy squared s. The recent measurements of $e^+e^- \to \text{VP}(\omega\pi^0, \rho\eta$ and $\rho\eta')$ from BES [13,14] investigated the s dependence of the cross sections and form factors in the energy range from 3.65 to 3.773 GeV. It is interesting to investigate the s dependence over a wider energy range. Since CLEO measured the cross section for $e^+e^- \to \phi\eta$ at CM energy $\sqrt{s} = 3.67$ GeV [8], a measurement of the same process at $\sqrt{s} = 10.58$ GeV provides a meaningful test of the s dependence.

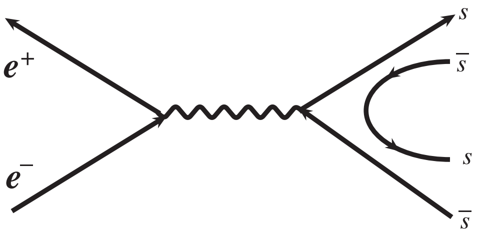

FIG. 1. Possible Feynman diagram for $e^+e^- \to \phi\eta$.

This analysis uses 204 fb^{-1} of e^+e^- colliding beam data collected on the $\Upsilon(4S)$ resonance at $\sqrt{s} = 10.58$ GeV and 20 fb^{-1} collected 40 MeV below the Υ(4S) mass with the *BABAR* detector at the SLAC PEP-II asymmetric-energy B factory. The *BABAR* detector is described in detail elsewhere [15]. Charged-particle momenta and energy loss are measured in the tracking system that consists of a silicon vertex tracker (SVT) and a drift chamber (DCH). Electrons and photons are detected in a CsI(Tl) calorimeter (EMC). An internally reflecting ring-imaging Cherenkov detector (DIRC) provides charged particle identification (PID). An instrumented magnetic flux return (IFR) provides identification of muons. Kaon and pion candidates are identified using likelihoods of particle hypotheses calculated from the specific ionization in the DCH and SVT and the Cherenkov angle measured in the DIRC. Photons are identified by shower shape and lack of associated tracks.

To reconstruct $\phi\eta$ in the $K^+K^-\gamma\gamma$ mode, events with exactly two well-reconstructed, oppositely charged tracks and at least two well-identified photons are selected. Charged tracks are required to have at least 12 DCH hits and a laboratory polar angle within the SVT acceptance, $0.41 < \theta < 2.54$ radians. The laboratory momenta of the kaon candidates are required to be greater than 800 MeV/c to reduce background. The two tracks selected must both be identified as kaons. We fit the two tracks to a common vertex, and require the χ^2 probability to exceed 0.1%. The photon candidates are required to have a minimum laboratory energy of 500 MeV. The invariant mass distribution of $K^+K^-\gamma\gamma$, after requiring the invariant mass of KK to be near the ϕ mass ($m_{KK} < 1.1$ GeV/c^2) and that of $\gamma\gamma$ to be near the η mass ($0.4 < m_{\gamma\gamma} < 0.8$ GeV/c^2) is shown in Fig. 2(a). We accept events with a reconstructed invariant mass of $K^+K^-\gamma\gamma$ within 230 MeV/c^2 of the e^+e^- CM energy. There is at most one entry per event in the region of interest.

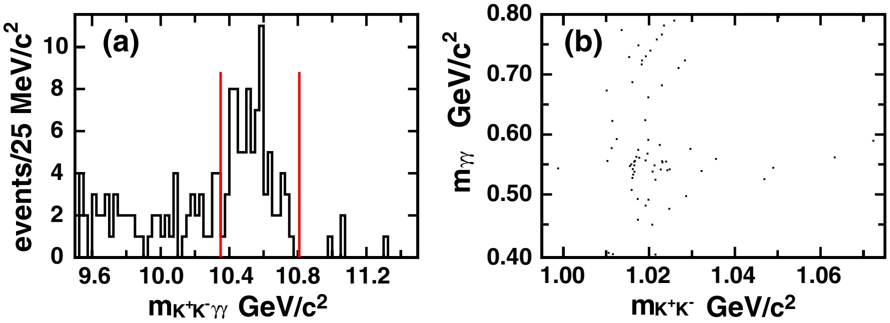

FIG. 2 (color online). (a) Distribution of the invariant mass ($\Upsilon(4S)$ data) for the $K^+K^-\gamma\gamma$ final state near the $\phi\eta$ region. The accepted signal region is indicated by the lines. (b) Scatter plot of the invariant masses of the K^+K^- and $\gamma\gamma$ pairs for those events in the accepted signal region.

Figure 2(b) shows the scatter plot of invariant masses of K^+K^- and $\gamma\gamma$ pairs from the accepted $e^+e^- \to K^+K^-\gamma\gamma$ events. The concentration of events indicates $\phi\eta$ production.

We use a two-dimensional log-likelihood fit to extract the signal for the reaction $e^+e^- \to \phi\eta$. Because of the fact that the final state particle masses are far below the e^+e^- collision energy, we may treat the two-body masses as uncorrelated. Justified by Fig. 2(b), the signal probability density function (PDF) is constructed as a product of two one-dimensional PDFs, one for each resonance. We use a P-wave relativistic Breit-Wigner formula to construct a PDF for the ϕ resonance and a Gaussian function to model the η resonance. A threshold function $q^3/(1 + q^3R_t)$ is used to model the background in the K^+K^- system, where q is the daughter momentum in the ϕ rest frame and R_t is a shape parameter. A linear function $(p_0 + p_1 \cdot m_{\gamma\gamma})$ is used to model the background under the η.

In the fit to data, we fix the mass and width of the ϕ and the mass of the η to the world average values [16]. The width of the η, 13.6 MeV, is fixed to the resolution obtained from simulation. The floating parameters in the fit are: R_t, p_0/p_1, and the numbers of events for all components—$\phi\eta$, $\phi\gamma\gamma$ and ηK^+K^-. The mass projections in KK and $\gamma\gamma$ from the two-dimensional fit are shown in Fig. 3(a) and 3(b), respectively. We define the ϕ mass window as $1.008 < m_{KK} < 1.035\ \text{GeV}/c^2$ to reduce the systematic uncertainty due to the long tail of ϕ masses. The extracted number of $\phi\eta$ signal events is 24 ± 5 in the ϕ mass window, with 20 ± 5 in the on-resonance sample and 3 ± 2 in the off-resonance sample. The number of background events within the ϕ mass window and within 3 standard deviations of the η mass is 7 ± 2. The significance is estimated by the log-likelihood difference between signal ($ln(L_s)$) and null ($ln(L_n)$) hypotheses (no $\phi\eta$ signal component in the PDF), $\sqrt{2ln(L_s/L_n)}$, which gives 6.5 standard deviations.

Given the negative C-parity of the $\phi\eta$ final state, we assume $\phi\eta$ is produced through one-virtual-photon annihilation. The angular distributions of $\phi\eta$ from a $\mathrm{J}^\mathrm{P} = 1^-$ initial state, in the helicity basis [17], can be calculated to be:

$$\frac{dN}{d\cos\theta^* d\cos\theta_\phi d\varphi_\phi} \propto \sin^2\theta_\phi(1 + \cos^2\theta^* + \cos2\varphi_\phi\sin^2\theta^*), \qquad (1)$$

where the production angle θ^* is defined as the angle between the ϕ meson direction and incident e^- beam in the CM frame. The ϕ helicity angle θ_ϕ is defined as the polar angle, measured in the ϕ rest frame, of the K^+ momentum direction with respect to an axis that is aligned with the ϕ momentum direction in the laboratory frame. The variable φ_ϕ is the K^+ azimuthal angle around the

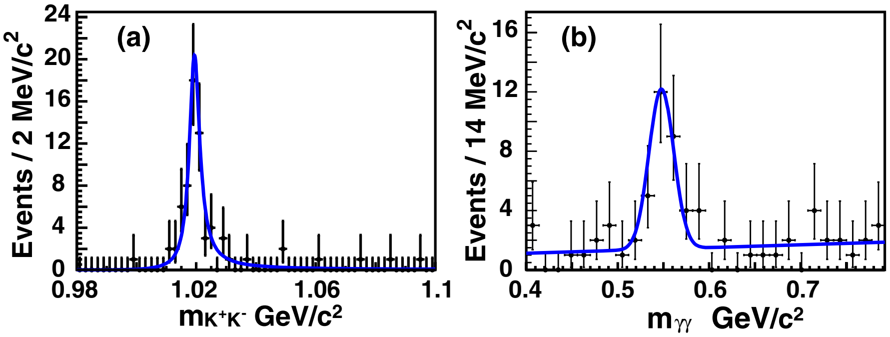

FIG. 3 (color online). Mass projections for (a) K^+K^- pairs and (b) $\gamma\gamma$ pairs in $K^+K^-\gamma\gamma$ events.

direction of the ϕ measured with respect to the plane formed by the ϕ and the incoming electron. The helicity and azimuthal angles of the pseudoscalar η are flat and thus not included in Eq. (1). Integrating over the other two angles, the distributions of the production angle, ϕ helicity and ϕ azimuthal angle are expected to be $1 + \cos^2\theta^*$, $\sin^2\theta_\phi$ and $2 + \cos 2\varphi_\phi$, respectively. The observed angular distributions from $e^+e^- \to \phi\eta$ data are consistent with the above expectation but the constraints on these angular distributions are limited by statistics.

The systematic uncertainty from the two-dimensional fit is estimated from the difference in yield obtained by floating the mean, width, and resolution parameters in the fit. The systematic uncertainties due to PID, tracking, and photon efficiency are estimated based on measurements from control data samples. The possible background from related modes with an extra π^0 was estimated to be small ($< 1\%$) by using extrapolations from statistically limited four-particle mass sidebands and we ignore it. The systematic uncertainties are summarized in Table I.

The radiation-corrected cross section for $e^+e^- \to \phi\eta$ is calculated from:

$$\sigma = \frac{N_{\mathrm{Observed}}}{\mathcal{L} \times \mathcal{B}(\phi \to \mathcal{K}\mathcal{K}) \times \mathcal{B}(\eta \to \gamma\gamma) \times \varepsilon^{\mathcal{MC}} \times (1 + \delta)} \tag{2}$$

where N_{Observed} is the extracted number of $\phi\eta$ signal events from on- and off-resonance data, $\mathcal{L}$ is the integrated luminosity, $\mathcal{B}(\phi \to KK)$ is the branching fraction of $\phi \to KK$, $\mathcal{B}(\eta \to \gamma\gamma)$ is the branching fraction of $\eta \to \gamma\gamma$, ε^{MC} is the signal efficiency obtained from Monte Carlo simulation (MC), and δ is the radiation correction calculated according to Ref. [18]. We obtain $(1 + \delta) = 0.768$. The uncertainties due to the theoretical model and the s dependence are negligible. The signal MC events are generated uniformly in phase space. For the determination of signal cross sections, the MC $\cos\theta^*$, $\cos\theta_\phi$ and φ_ϕ distributions are reweighted using Eq. (1). The signal efficiency in the fiducial region of $|\cos\theta^*| < 0.8$ for $\phi\eta$ without radiative correction is estimated to be 34.3%, including corrections to MC simulation for PID and tracking. Taking the branching fraction of $\phi \to K^+K^-$ as 49.1%, and $\eta \to \gamma\gamma$ as 39.4% [16], the final radiation-corrected cross section for $1.008 < m_\phi < 1.035\ \mathrm{GeV}/c^2$ within $|\cos\theta^*| < 0.8$ near $\sqrt{s} = 10.58$ GeV is:

$$\sigma_{\mathrm{fid}}(e^+e^- \to \phi\eta) = 2.1 \pm 0.4(\mathrm{stat}) \pm 0.1(\mathrm{syst})\ \mathrm{fb}.$$

The cross section within $\cos\theta^* \in [-0.8, 0.8]$ can be scaled to $\cos\theta^* \in [-1.0, 1.0]$ by assuming a $1 + \cos^2\theta^*$ distribution to obtain:

$$\sigma(e^+e^- \to \phi\eta) = 2.9 \pm 0.5(\mathrm{stat}) \pm 0.1(\mathrm{syst})\ \mathrm{fb}.$$

To study the possibility that the observed signal is due to $\Upsilon(4S)$ decay, we scale the off-resonance signal to the on-resonance luminosity, and subtract it from the on-resonance signal. The resulting number of events, -10 ± 21, is consistent with zero. The corresponding branching fraction for $\Upsilon(4S) \to \phi\eta$ is $(-0.9 \pm 1.8) \times 10^{-6}$. Assuming this uncertainty can be treated as Gaussian and normalizing to the physical region (≥ 0), the 90% confidence level upper limit is 2.5×10^{-6}.

There is currently no direct prediction for the cross section of this process at this energy, but the $e^+e^- \to$ VP cross section is expected to have $1/s^4$ [10,11] dependence in QCD-based models.. A comparison between our result and that of CLEO, ($\sigma = 2.1^{+1.9}_{-1.2} \pm 0.2$ pb) at $\sqrt{s} = 3.67$ GeV (continuum) [8], favors a $1/s^3$ dependence (Fig. 4). We quantify the degree to which $1/s^4$ scaling is disfavored by scaling our measured cross section in this fashion to $\sqrt{s} = 3.67$ GeV, and comparing it to the CLEO measurement. Note, however, that if CLEO did have a downward statistical fluctuation, both their central value and their uncertainty would be low. Accordingly, the uncertainty we use in this comparison is the CLEO one scaled by the square root of the ratio, 2.6, of the predicted to the observed cross sections. The resulting disagreement with $1/s^4$ scaling is approximately 2 standard deviations.

The form of the s dependence has important theoretical implications, which may affect a wide range of QCD-based processes such as $e^+e^- \to$ VP [10], exclusive hadronic B

TABLE I. Systematic uncertainties on the cross section of $\phi\eta$.

Source	Systematic uncertainty %
Photon efficiency	3.6
Two-dimensional fit	1.3
Particle Identification	3.0
Tracking efficiency	2.6
Luminosity	2.0
Total	6.0

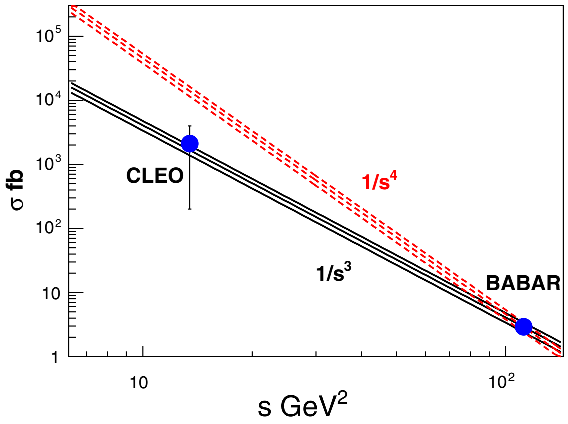

FIG. 4 (color online). Cross section extrapolations based on *BABAR*'s measurement at $\sqrt{s} = 10.58$ GeV assuming $1/s^3$ (black) or $1/s^4$ (red) energy dependence. The bands show 1 standard deviation uncertainties in the extrapolations. The CLEO measurement at $\sqrt{s} = 3.67$ GeV is also shown.

decays [19], and charmonium decays [20]. The large initial-state radiation sample at the B factories can provide another route to test the s dependence over a wider energy range. A direct comparison of the absolute cross section with a possible theoretical calculation [9] is also interesting.

In summary, we have observed the exclusive production of $\phi\eta$ in e^+e^- interactions at $\sqrt{s} = 10.58$ GeV. Combining with CLEO's measurement and interpreting our result as continuum production, the measured $\phi\eta$ cross section favors $1/s^3$ dependence, which is in conflict with some QCD-based predictions. The 90% confidence level upper limit on the branching fraction $\mathcal{B}(\Upsilon(4S) \rightarrow \phi\eta)$ is 2.5×10^{-6}.

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