Observation of $Y(2175)$ in $J/\psi \to \eta\phi f_0(980)$

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The decays of $J/\psi \to \eta\phi f_0(980)[\eta \to \gamma\gamma, \phi \to K^+K^-, f_0(980) \to \pi^+\pi^-]$ are analyzed using a sample of 5.8×10^7 J/ψ events collected with the BESII detector at the Beijing Electron-Positron Collider. A structure at around 2.18 GeV/c^2 with about 5σ significance is observed in the $\phi f_0(980)$ invariant mass spectrum. A fit with a Breit-Wigner function gives the peak mass and width of $m = 2.186 \pm 0.010(\text{stat}) \pm 0.006(\text{syst})$ GeV/c^2 and $\Gamma = 0.065 \pm 0.023(\text{stat}) \pm 0.017(\text{syst})$ GeV/c^2, respectively, which are consistent with those of $Y(2175)$, observed by the *BABAR* Collaboration in the initial-state radiation process $e^+e^- \to \gamma_{\text{ISR}}\phi f_0(980)$. The production branching ratio is determined to be $\text{Br}(J/\psi \to \eta Y(2175))\text{Br}(Y(2175) \to \phi f_0(980))\text{Br}(f_0(980) \to \pi^+\pi^-) = [3.23 \pm 0.75(\text{stat}) \pm 0.73(\text{syst})] \times 10^{-4}$, assuming that the $Y(2175)$ is a 1^{--} state.

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A new structure, denoted as $Y(2175)$ and with mass $m = 2.175 \pm 0.010 \pm 0.015$ GeV/c^2 and width $\Gamma = 58 \pm 16 \pm 20$ MeV/c^2, was observed by the *BABAR* experiment in the $e^+e^- \to \gamma_{\text{ISR}}\phi f_0(980)$ initial-state radiation process [1,2]. This observation stimulated some theoretical speculation that this $J^{PC} = 1^{--}$ state may be an s-quark version of the $Y(4260)$ since both of them are produced in e^+e^- annihilation and exhibit similar decay patterns [3].

There have been a number of different interpretations proposed for the $Y(4260)$, including a $c\bar{c}g$ hybrid [4–6]; a $4\,^3S_1$ $c\bar{c}$ state [7]; a $[cs]_S[\bar{c}\,\bar{s}]_S$ tetraquark state [8]; or baryonium [9]. Likewise, a $Y(2175)$ has correspondingly been interpreted as a $s\bar{s}g$ hybrid [10]; a $2\,^3D_1 s\bar{s}$ state [11]; or a $s\bar{s}s\bar{s}$ tetraquark state [12]. As of now, none of these interpretations have been either established or ruled out by experiment.

In this Letter we report the observation of the $Y(2175)$ in the decays of $J/\psi \to \eta\phi f_0(980)$, with $\eta \to \gamma\gamma$, $\phi \to K^+K^-$, $f_0(980) \to \pi^+\pi^-$, using a sample of 5.8×10^7 J/ψ events collected with the upgraded Beijing Spectrometer (BESII) detector at the Beijing Electron-Positron Collider (BEPC).

BESII is a large solid-angle magnetic spectrometer that is described in detail in Ref. [13]. Charged particle momenta are determined with a resolution of $\sigma_p/p = 1.78\%\sqrt{1+p^2}$ in a 40-layer cylindrical drift chamber. Particle identification is accomplished using specific ionization (dE/dx) measurements in the main drift chamber (MDC) and time-of-flight (TOF) measurements in a barrel-like array of 48 scintillation counters. The dE/dx resolution is $\sigma_{dE/dx} = 8.0\%$, and the TOF resolution is $\sigma_{\rm TOF} =$ 180 ps for Bhabha tracks. Outside of the time-of-flight counters is a 12-radiation-length barrel shower counter (BSC) composed of gas tubes interleaved with lead sheets. The BSC measures the energies and directions of photons with resolutions of $\sigma_E/E \simeq 21\%/\sqrt{E({\rm GeV})}$, $\sigma_\phi =$ 7.9 mrad, and $\sigma_z = 2.3$ cm. The iron flux return of the magnet is instrumented with three double layers of counters that are used to identify muons.

In this analysis, a GEANT3-based Monte Carlo (MC) package with detailed consideration of the detector performance is used. The consistency between data and MC has been validated using many high purity physics channels [14]. For $J/\psi \to \eta Y(2175)[Y(2175) \to \phi f_0(980), f_0(980) \to \pi^+\pi^-]$, a Monte Carlo generator assumes the $Y(2175)$ quantum numbers to be $J^{PC} = 1^{--}$ and considers the angular distributions for $1^{--} \to 0^{-+} + 1^{--}$; $1^{--} \to 1^{--} + 0^{++}$ is used to determine the detection efficiency.

For a candidate event, we require four good charged tracks with zero net charge. A good charged track is one that can be well fitted to a helix within the polar angle region $|\cos\theta| < 0.8$ and has a transverse momentum larger than 70 MeV/c. For each charged track, the TOF and dE/dx information are combined to form particle identification confidence levels for the π, K, and p hypotheses; the particle type with the highest confidence level is assigned to each track. The four charged tracks are required to consist of an unambiguously identified $K^+K^-\pi^+\pi^-$ combination. Candidate photons are required to have an energy deposited in the BSC that is greater than 60 MeV and to be isolated from charged tracks by more than 5°; at least two photons are required. A four-constraint energy-momentum conservation kinematic fit is performed to the $K^+K^-\pi^+\pi^-\gamma\gamma$ hypothesis, and the χ^2_{4C} is required to be less than 15. For events with more than two selected photons, the combination with the smallest χ^2 is chosen. An η signal is evident in the $\gamma\gamma$ invariant mass spectrum [Fig. 1(a)]; $\eta \to \gamma\gamma$ candidates are defined as γ pairs with $|M_{\gamma\gamma} - 0.547| < 0.037$ GeV/c^2. A ϕ signal is distinct in the K^+K^- invariant mass spectrum [Fig. 1(b)], and for these candidates, we require $|m_{K^+K^-} - 1.02| <$ 0.019 GeV/c^2. In the $\pi^+\pi^-$ invariant mass spectrum, candidate $f_0(980)$ mesons are defined by $|m_{\pi^+\pi^-} - 0.980| < 0.060$ GeV/c^2 [Fig. 1(c)]. The $\phi f_0(980)$ invariant mass spectrum for the selected events is shown in Fig. 2(a), where a clear enhancement is seen around 2.18 GeV/c^2.

The Dalitz plot of $m^2_{\eta f_0(980)}$ versus $m^2_{\eta\phi}$ for the selected events is shown in Fig. 2(b), where a diagonal band can be

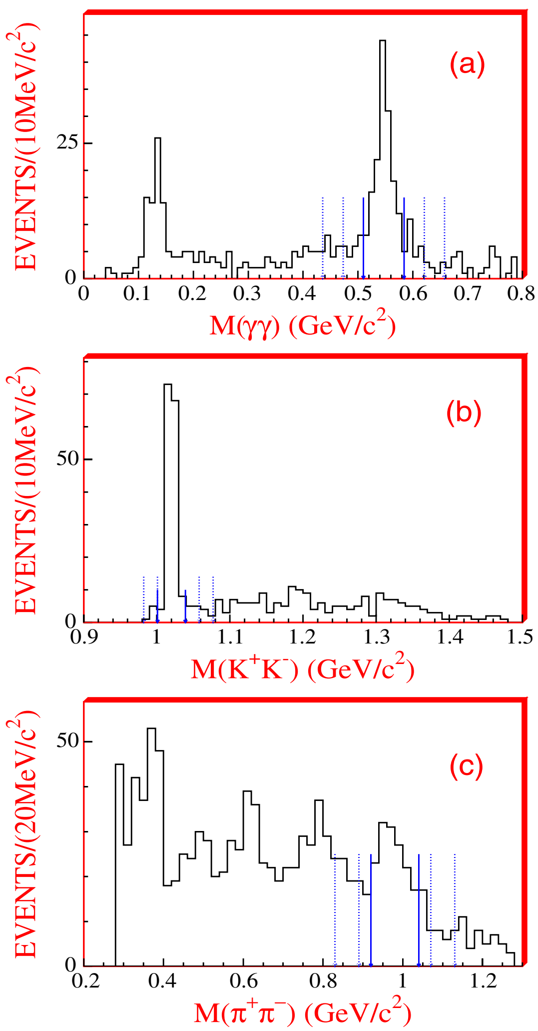

FIG. 1 (color online). (a) The $\gamma\gamma$ invariant mass spectrum. (b) The K^+K^- invariant mass spectrum. (c) The $\pi^+\pi^-$ invariant mass spectrum. The solid arrows in each plot show the cuts imposed for η, ϕ, and f_0 selection. The dashed arrows show the sideband regions used to estimate background levels.

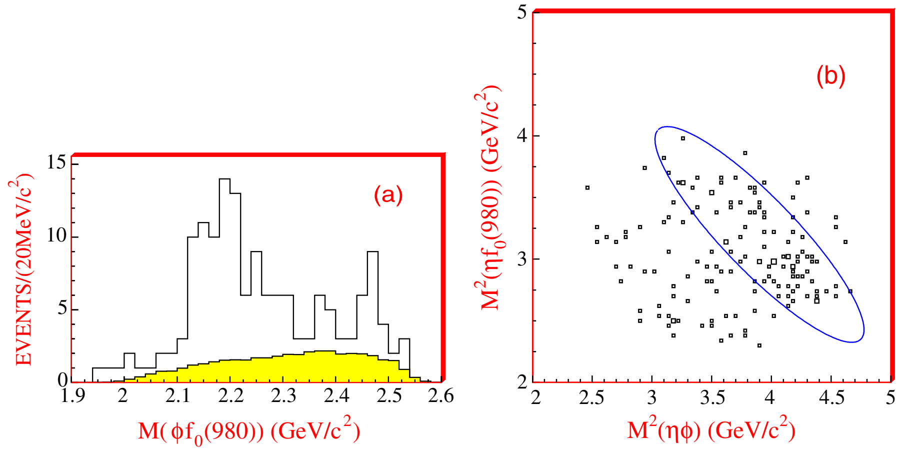

FIG. 2 (color online). (a) The $\phi f_0(980)$ invariant mass spectrum. The open histogram is data and the shaded histogram is $J/\psi \to \eta\phi f_0(980)$ phase-space MC events (with arbitrary normalization). (b) The Dalitz plot of $m^2_{\eta f_0(980)}$ versus $m^2_{\eta\phi}$. The ellipse shows the resonance band in the $\phi f_0(980)$ invariant mass spectrum.

seen. This band corresponds to the structure observed around 2.18 GeV$/c^2$ in the $\phi f_0(980)$ invariant mass spectrum shown in Fig. 2(a).

To clarify the origin of the observed structure, we have made extensive studies of potential background processes using both data and MC. Non-η or non-$f_0(980)$ processes are studied with η-$f_0(980)$ mass sideband events (0.074 GeV$/c^2 < |M_{\gamma\gamma} - 0.547| < 0.111$ GeV$/c^2$ or 0.090 GeV$/c^2 < |m_{\pi^+\pi^-} - 0.980| < 0.150$ GeV$/c^2$). Non-ϕ processes are studied with ϕ mass sideband events [0.038 GeV$/c^2 < (m_{K^+K^-} - 1.02) < 0.057$ GeV$/c^2$ or -0.038 GeV$/c^2 < (m_{K^+K^-} - 1.02) < -0.019$ GeV$/c^2$]. The scaled $M_{\pi^+\pi^-K^+K^-}$ distribution for the summed total of sideband events (minus double counting) are shown as a shaded histogram in Fig. 3. No structure around 2.18 GeV$/c^2$ is evident. In addition, we also checked for possible backgrounds from various J/ψ decays using Monte Carlo simulation, and no evidence of a structure at 2.18 GeV$/c^2$ is observed.

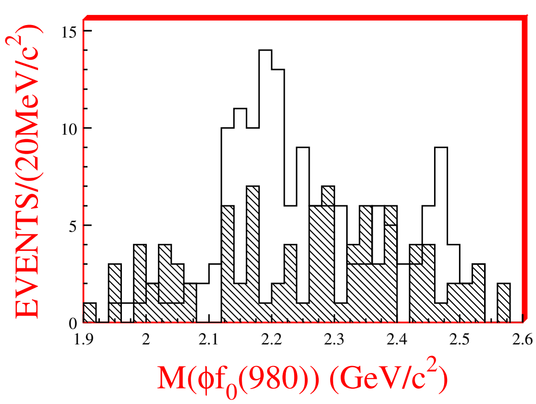

FIG. 3 (color online). The $\phi f_0(980)$ invariant mass spectrum. The open histogram is data and the shaded histogram shows the sideband-determined background.

We fit the $\phi f_0(980)$ invariant mass spectrum [see Fig. 2(a)] and the total sidebands (see Fig. 3) simultaneously. The procedure is as follows: First we fit the sideband distribution with a third-order polynomial. Next we use the polynomial shape as the background function for both the $\phi f_0(980)$ invariant mass spectrum histogram and the total sideband histogram, and the signal and background normalizations are allowed to float. In this fit, the normalization for the background polynomial is constrained to be the same for both the signal and sideband histograms. We use a constant-width Breit-Wigner (BW) convolved with a Gaussian mass resolution function (with $\sigma = 12$ MeV$/c^2$) to represent the $Y(2175)$ signal. The mass and width obtained from the fit (shown as smooth curves in Fig. 4) are $m = 2.186 \pm 0.010$(stat) GeV$/c^2$ and $\Gamma = 0.065 \pm 0.023$(stat) GeV$/c^2$. The fit yields 52 ± 12 signal events and $-2\ln L$ (L is the likelihood value of the fit) $= 78.6$. A fit to the mass spectrum without a BW signal function returns $-2\ln L = 116.0$. The change in $-2\ln L$ with a change of degrees of freedom $= 3$ corresponds to a statistical significance of 5.5σ for the signal.

Using the MC-determined selection efficiency of 1.44%, we find the product branching ratio to be:

$$\mathrm{Br}(J/\psi \to \eta Y(2175)) \times \mathrm{Br}(Y(2175) \to \phi f_0(980)) \times \mathrm{Br}(f_0(980) \to \pi^+\pi^-) = (3.23 \pm 0.75) \times 10^{-4}.$$

Fits that use different treatments for the background are also tried. If the background is fitted as a third-order polynomial with all parameters allowed to float, the signal yield is 61 ± 14 events, with mass and width of $m = 2.182 \pm 0.010$(stat) GeV$/c^2$ and $\Gamma = 0.073 \pm 0.024$(stat) GeV$/c^2$, respectively. The statistical significance is 4.9σ. If the background shape is fixed to the shape of phase space, the fit yields 57 ± 13 signal events, with a

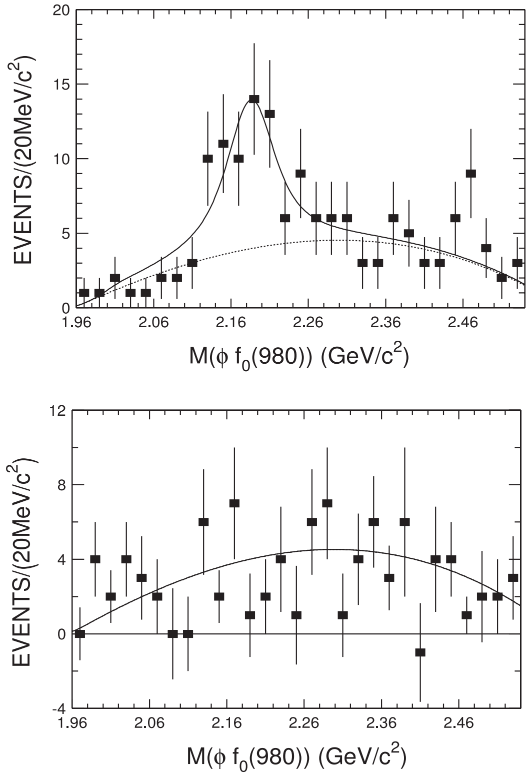

FIG. 4. The top panel shows the fit (solid curve) to the data (points with error bars); the dashed curve indicates the background function. The bottom panel shows the simultaneous fit to the sideband events (points with error bars) with the same background function. The background normalizations for the two plots are constrained to be equal.

statistical significance of 5.3σ. The mass and width obtained are $m = 2.182 \pm 0.009(\text{stat})\ \text{GeV}/c^2$ and $\Gamma = 0.069 \pm 0.022(\text{stat})\ \text{GeV}/c^2$. For all of the background shapes considered, the fitted masses and widths of the signal are consistent with each other. We take the results with the background shape fixed to the sideband shape as the central values.

We determine the systematic uncertainties of the mass and width measurements by varying the functional form used to represent the background, the fitting range of the invariant mass spectrum, the bin width of the invariant mass spectrum, allowing the sideband and signal background normalizations to differ, and including possible fitting biases. The latter are estimated from the differences between the input and output mass and width values from a MC study. Adding each contribution in quadrature, the total systematic errors on the mass and width are $6\ \text{MeV}/c^2$ and $17\ \text{MeV}/c^2$, respectively. The systematic error on the branching ratio measurement comes mainly from the uncertainties in the MDC simulation (including systematic uncertainties of the tracking efficiency and the kinematic fits), the photon detection efficiency, the particle identification efficiency, the η decay branching ratio to $\gamma\gamma$ and the ϕ decay branching ratio to K^+K^-, the background function, the fitting range of the invariant mass spectrum, the bin width of the invariant mass spectrum, the fitting method, and the total number of J/ψ events [15]. Adding all contributions in quadrature gives a total systematic error on the product branching ratio of 22.7%.

We studied the small peak near $2.47\ \text{GeV}/c^2$ in the $\phi f_0(980)$ invariant mass spectrum [see Fig. 2(a)], which was also noted by *BABAR* [2]. A fit was made to the $\phi f_0(980)$ invariant mass spectrum using two noninterfering Breit-Wigner functions with mass and width of the second peak fixed to the *BABAR* fitted results: $2.47\ \text{GeV}/c^2$ and $0.077\ \text{GeV}/c^2$ [2], respectively. The fit results indicate a significance for the first peak of 5.8σ, with a mass and width of $m = 2.186 \pm 0.010(\text{stat})\ \text{GeV}/c^2$ and $\Gamma = 0.065 \pm 0.022(\text{stat})\ \text{GeV}/c^2$, respectively. The statistical significance of the second peak is only 2.5σ.

In summary, the $J/\psi \to \eta\phi f_0(980)$ decay process with $\eta \to \gamma\gamma$, $\phi \to K^+K^-$, and $f_0(980) \to \pi^+\pi^-$ has been analyzed. A structure, the $Y(2175)$, is observed with about 5σ significance in the $\phi f_0(980)$ invariant mass spectrum. From a fit with a Breit-Wigner function, the mass is determined to be $M = 2.186 \pm 0.010(\text{stat}) \pm 0.006(\text{syst})\ \text{GeV}/c^2$, the width is $\Gamma = 0.065 \pm 0.023(\text{stat}) \pm 0.017(\text{syst})\ \text{GeV}/c^2$ and the product branching ratio is $\text{Br}(J/\psi \to \eta Y(2175))\text{Br}(Y(2175) \to \phi f_0(980))\text{Br}(f_0(980) \to \pi^+\pi^-) = [3.23 \pm 0.75(\text{stat}) \pm 0.73(\text{syst})] \times 10^{-4}$. The mass and width are consistent with *BABAR*'s results. The identification of the precise nature of the $Y(2175)$ requires measurements of additional decay channels [10,11]. This is the subject of the work that is currently in progress.

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