Evidence for the decay $B^0 \rightarrow \omega \omega$ and search for $B^0 \rightarrow \omega \phi$

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Charmless decays of $B$ mesons to two vector mesons have been of significant recent interest, in part because of the unexpectedly small value of the longitudinal polarization component observed in $B \to \phi K^*$ decays [1, 2]. The resulting large transverse spin component could be due either to unanticipated large Standard Model (SM) contributions [3] or to non-SM effects [4]. Further information and SM constraints on these decays can be obtained from measurements of, or limits on, the branching fractions of related decays, such as $B^0 \to \omega \omega$ and $B^0 \to \omega \phi$ [5]. These latter decays are also important because they contain relatively unstudied $b \to d$ quark transitions ($B^0 \to \omega \omega$ however is expected to be dominated by $b \to u$ transitions) and are sensitive to the phase angles $\alpha$ and $\gamma$ of the Cabibbo-Kobayashi-Maskawa quark mixing matrix [6]. Deviations of the observed branching fractions from their SM expectations could provide evidence for physics beyond the SM.

Theoretical predictions for the SM branching fractions lie in the range $(0.5 - 3) \times 10^{-6}$ for $B^0 \to \omega \omega$ and $(0.01 - 2) \times 10^{-6}$ for $B^0 \to \omega \phi$ [3]. Previous limits on these branching fractions are presented in Refs. [8, 9]. The results from Ref. [9], $B(B^0 \to \omega \omega) < 4.0 \times 10^{-6}$ and $B(B^0 \to \omega \phi) < 1.2 \times 10^{-6}$, are based on about half the final BABAR data sample. In this Letter, we update the results of Ref. [9] using the final BABAR dataset and improved analysis techniques.

Due to the limited size of the data sample, there is insufficient precision to determine the decay polarization in $B^0 \to \omega \omega$ or $B^0 \to \omega \phi$. We therefore integrate over the angular distributions, correcting for detector acceptance and efficiency. The angular distribution is

$$\frac{d^2 \Gamma}{\Gamma d \cos \theta_{V_1} d \cos \theta_{V_2}} = \frac{9}{4} \left( 1 - f_L \right) \sin^2 \theta_{V_1} \sin^2 \theta_{V_2} + f_L \cos^2 \theta_{V_1} \cos^2 \theta_{V_2}$$

where $V_{1,2} = (\{\omega, \omega\} \text{ or } \{\omega, \phi\})$ are vector mesons, $\theta_{V_{1,2}}$ are helicity angles, and $f_L$ is the fraction of events with longitudinal spin polarization. For the $\phi$ meson, $\theta_{\phi}$ is the angle in the $\phi$ rest frame between the positively charged kaon and the boost from the $B$ rest frame, whereas for
TABLE I: Selection requirements on the invariant mass of \( B\)-daughter intermediate states.

| State   | Inv. mass (MeV) |
|---------|-----------------|
| \( \pi^0 \) | \( 120 < m_{\gamma\gamma} < 150 \) |
| \( \omega \) | \( 740 < m_{\pi\pi\pi} < 820 \) |
| \( \phi \) | \( 1009 < m_{\pi\pi\pi} < 1029 \) |

The data were collected with the \textit{BaBar} detector \cite{bib:BaBar} at the PEP-II asymmetric-energy \( e^+e^- \) collider located at the SLAC National Accelerator Laboratory. An integrated luminosity of 429 fb\(^{-1}\) \cite{bib:BaBar}, corresponding to \( N_{B\bar{B}} = (471 \pm 3) \times 10^6 \) \( B\bar{B} \) pairs, was recorded at the \( \Upsilon(4S) \) resonance (center-of-mass energy \( \sqrt{s} = 10.58 \) GeV). Charged particles are detected, and their momenta measured, by five layers of double-sided silicon microstrip detectors and a 40-layer drift chamber, both operating in the 1.5 T magnetic field of a superconducting solenoid. We identify photons and electrons using a CsI(Tl) electromagnetic calorimeter. Charged particle identification (PID) is provided by energy loss measurements in the tracking detector and by a ring-imaging Cherenkov detector.

We reconstruct the vector-meson decays through the \( \omega \to \pi^+\pi^-\pi^0 \) and \( \phi \to K^+K^- \) channels, with \( \pi^0 \to \gamma\gamma \). The minimum laboratory energy (momentum) required for photons (charged kaons) is 50 MeV (100 MeV). There is no specific minimum momentum requirement for charged pions but they generally respect \( p_T > 50 \) MeV. Charged pion and kaon candidates are rejected if their PID signature satisfies tight consistency with protons or electrons, and the kaons must have a kaon signature, while the pions must not. We require all charged particle products associated with the \( B \) meson candidate decay to be consistent with having originated at a common vertex.

We apply the invariant mass requirements listed in Table I for the \( \pi^0, \omega, \) and \( \phi \) mesons. After selection, the \( \pi^0 \) is constrained to its nominal mass \cite{bib:BaBar}, which improves the \( \omega \) mass resolution. The restrictions on the \( \omega \) and \( \phi \) meson masses are loose enough to incorporate sideband regions.

A \( B \) meson candidate is characterized kinematically by the energy-substituted mass \( m_{ES} = \sqrt{(1/s + \mathbf{p}_0 \cdot \mathbf{p}_B)^2/E_0^2 - \mathbf{p}_B^2} \) and the energy difference \( \Delta E = E_B - \sqrt{s}/2 \), where \( (E_0, \mathbf{p}_0) \) and \( (E_B, \mathbf{p}_B) \) are the four-momenta of the \( \Upsilon(4S) \) and the \( B \) candidate, respectively, and the asterisk denotes the \( \Upsilon(4S) \) rest frame (quantities without asterisks are measured in the laboratory frame). For correctly reconstructed signal candidates, \( \Delta E \) and \( m_{ES} \) peak at values of zero and \( m_B \), respectively, with resolutions of about 30 MeV and 3.0 MeV. Thus, signal events for this analysis mostly fall in the regions \( |\Delta E| \leq 0.1 \) GeV and \( 5.27 \leq m_{ES} \leq 5.29 \) GeV. To incorporate sideband regions, we require \( |\Delta E| \leq 0.2 \) GeV and \( 5.24 \leq m_{ES} \leq 5.29 \) GeV. The average number of candidates found per selected event is 1.3 for \( B^0 \to \omega\phi \) decays and 1.7 for \( B^0 \to \omega\phi \) decays. We choose the candidate with the smallest \( \chi^2 \) value constructed from the deviations of the \( \omega \) and \( \phi \) resonance masses from their nominal values \cite{bib:BaBar}.

Backgrounds arise primarily from random combinations of particles in continuum events \( (e^+e^- \to q\bar{q}, \) with \( q = u, d, s, c). We reduce this background by using the angle \( \theta_T \) in the \( \Upsilon(4S) \) rest frame between the thrust axis \cite{bib:BaBar} of the \( B \) candidate and the thrust axis of the other charged and neutral particles in the event. The distribution of \( |\cos \theta_T| \) is sharply peaked near 1.0 for \( q\bar{q} \) pairs, and nearly uniform for \( B \) meson decays. We require \( |\cos \theta_T| < 0.9 \) for \( B^0 \to \omega\phi \) and \( |\cos \theta_T| < 0.8 \) for \( B^0 \to \omega\omega \).

We employ a maximum-likelihood fit, described below, to determine the signal and background yields. For the purposes of this fit, we construct a Fisher discriminant \cite{bib:BaBar} \( F \) that combines four variables defined in the \( \Upsilon(4S) \) frame: the polar angles with respect to the beam axis of the \( B \) meson momentum and \( B \) thrust axis, and the zeroth and second angular moments \( L_0 \) and \( L_2 \) of the energy flow about the \( B \) thrust axis. The moments are defined by \( L_j = \sum_i p_i \times |\cos \theta_i|^{j+1} \), where \( \theta_i \) is the angle with respect to the \( B \) thrust axis of a charged or neutral particle \( i \), \( p_i \) is its momentum, and the sum excludes the \( B \) candidate daughters.

From simulated event samples produced with Monte Carlo (MC) event generators \cite{bib:Mc}, we identify the most important backgrounds that arise from other \( B\bar{B} \) decay modes. Most of the \( B\bar{B} \) background does not peak in \( m_{ES} \) or \( \Delta E \) and is grouped with continuum events into a “combinatoric” background category. Other \( B\bar{B} \) decay modes, such as \( B^0 \to \omega\pi^0, B^0 \to \omega\phi\pi^0, B^0 \to \omega\rho\pi, B^0 \to \omega\omega_1, etc., \) peak in \( m_{ES} \) and/or \( \Delta E \) and are referred to as “peaking” background. All peaking modes are grouped together into a single background component, with a broad peak centered at negative values of \( \Delta E \), and which is fitted in data simultaneously with the signal and combinatoric background components.

We obtain signal and background yields from extended unbinned maximum-likelihood fits with input observables \( \Delta E, m_{ES}, F, \) and, for the vector meson \( V = \omega \) or \( \phi \), the mass \( m_V \) and the cosine of the helicity angle \( \cos \theta_V \). For each \( \omega \) meson, there is an additional helicity angle input observable, \( \cos \Phi_{\omega} \), provided by the polar angle, with respect to the \( \omega \) flight direction, of the \( \pi^0 \) in the \( \pi^+\pi^- \) rest frame. This angle is uncorrelated with the other input observables and has a distribution that is proportional to \( \sin^2 \Phi_{\omega} \) for signal. For background, the
angular distribution is nearly flat in $\cos \Phi_q$, and its deviation from flatness is parameterized by separate third-order polynomials for combinatoric and for peaking $B\bar{B}$ backgrounds. For each event $i$ and component $j$ (signal, combinatoric background, peaking $B\bar{B}$ background) we define the probability density function (PDF)

$$
P_j^i = P_j(m_{ES}^i)P_j(\Delta E^i)P_j(\mathcal{F}^i) \times \nonumber$$

$$
P_j(m_{V_1}^i, m_{V_2}^i, \cos \theta_{\phi_1}^i, \cos \theta_{\phi_2}^i) \times$$

$$
P_j(\cos \Phi_{\delta_1}^i)P_j(\cos \Phi_{\delta_2}^i),$$

where the last of the $P_j$ terms is not present for $B^0 \rightarrow \phi \omega$. The likelihood function is

$$
L = \frac{e^{-(\sum Y_j)}}{N!} \prod_{i=1}^{N} \sum Y_j P_j^i,$$

where $Y_j$ is the event yield for component $j$ and $N$ is the number of events in the sample.

For signal events, the PDF factor

$$
P_{sig}(m_{V_1}^i, m_{V_2}^i, \cos \theta_{\phi_1}^i, \cos \theta_{\phi_2}^i)$$

takes the form

$$
P_{1,sig}(m_{V_1}^i)P_{2,sig}(m_{V_2}^i)Q(\cos \theta_{\phi_1}^i, \cos \theta_{\phi_2}^i),$$

where $Q$ corresponds to the right-hand side of Eq. (1) after modification to account for detector acceptance. For combinatoric background events, the PDF factor is given for each vector meson independently by

$$
P_{cont}(m_{V}^i, \cos \theta_{\phi}^i) = \nonumber$$

$$
P_{peak}(m_{V}^i)P_{peak}(\cos \theta_{\phi}^i) + P_{cont}(m_{V}^i)P_{cont}(\cos \theta_{\phi}^i),$$

distinguishing between genuine resonance ($P_{peak}$) and combinatorial ($P_{cont}$) components. The background PDFs $P_{peak}(\cos \theta_{\phi}^i)$ and $P_{cont}(\cos \theta_{\phi}^i)$ are given by separately fitted third-order polynomials. For the peaking $B\bar{B}$ background, we assume that all four mass and helicity angle observables are independent.

To describe the PDFs for signal, we use the sum of two Gaussians for $P_{sig}(m_{ES})$ and for $P_{sig}(\Delta E)$. An asymmetric Gaussian is used for $P_{sig}(\mathcal{F})$, i.e., two half-Gaussian distributions (one on the right side of the mean and one on the left side) with different values for the standard deviation, summed with a small additional Gaussian component to account for misreconstructed signal events. The $m_{ES}$, $\Delta E$, and $\mathcal{F}$ PDFs for peaking $B\bar{B}$ background have the same functional form as for signal events, but their parameters are determined separately. The genuine resonance components of $P_j(m_{V})$ are both described by relativistic Breit-Wigner distributions, each convolved with the sum of two Gaussians to account for detector resolution, while the combinatoric components of $P_j(m_{V})$ are described by third-order polynomials. For the combinatoric background category, the $m_{ES}$ distribution is characterized by an ARGUS function $A(m_{ES}) \propto x \exp \left[ -\xi(x^2 - 1) \right]$ (with $x = m_{ES}/E_{p}^{0}$) [17], the $\Delta E$ distribution by a second-order polynomial, and the $\mathcal{F}$ distribution by an asymmetric Gaussian summed with an additional Gaussian. The background PDF parameters that are allowed to vary in the fit are the ARGUS function parameter $\xi$ for $m_{ES}$, the polynomial coefficients describing the combinatorial and the peaking $B\bar{B}$ components for $\Delta E$ and $m_{V}$, and the $B\bar{B}$ peak position and the two standard-deviation parameters of the asymmetric Gaussian for $\mathcal{F}$.

For signal events, the PDF parameters are determined from simulation. We study large control samples of $B \rightarrow D^{(*)}X$ events with similar topology to the signal modes, such as $B^0 \rightarrow D^-\rho^+$, to verify the simulated resolutions in $m_{ES}$ and $\Delta E$. We make (small) adjustments to the signal PDFs to account for any differences that are found.

In the fit to data, 13 parameters (out of around 130) are allowed to vary for each mode including the yields $Y_j$ of the signal, total peaking $B\bar{B}$ background, and total combinatoric background, and ten parameters of the continuum background PDFs. For both modes, we set $f_L$ to 0.88, a value consistent with theoretical expectations [10]. The event yields with their statistical uncertainties are presented in Table [II].

We evaluate possible biases in the signal yields, which might arise as a consequence of neglected correlations between the discriminating variables, by applying our fit to an ensemble of simulated experiments. The numbers of signal and peaking $B\bar{B}$ background events in these samples are Poisson-distributed around the observed values and are extracted randomly from MC samples that include simulation of the detector. The largest of the correlations (approximately 15%) is between the analysis variables $m_{ES}$ and $\Delta E$. The signal yield bias $Y_{bias}^{sig}$ we find for each mode is provided in Table [II].

The resulting branching fractions are calculated as

$$
B = \frac{Y_{sig} - Y_{bias}^{sig}}{e N_{B\bar{B}}},
$$

where the signal efficiencies $e$ are evaluated using MC and data control samples. The total number of $B\bar{B}$ pairs in data $N_{B\bar{B}}$ is evaluated using a dedicated analysis [18].

The systematic uncertainties on the branching fractions are summarized in Table [III]. The uncertainty attributed to the yield-bias correction is taken to be the quadrature sum of two terms: half of the bias correction and the statistical uncertainty on the bias itself. The uncertainties of PDF parameters that are fixed in the fit are evaluated by taking the difference between the respective parameter values determined in fits to simulated and observed $B \rightarrow D^{(*)}X$ events. Varying the signal PDF parameters within these uncertainties, we estimate yield uncertainties for each mode. Similarly, the uncertainty due
TABLE II: Fitted signal yield \( Y_{\text{sig}} \) and its statistical uncertainty, signal yield bias \( Y_{\text{sig}}^{\text{bias}} \), peaking \( B\bar{B} \) and combinatoric background yields \( Y_{\text{peak}} \) and \( Y_{\text{comb}} \) and their statistical uncertainties, signal detection efficiency \( \epsilon \) and its statistical uncertainty, daughter branching fraction product \( \prod B_i \) and its total uncertainty, significance \( S \) (with systematic uncertainties included), measured branching fraction \( B \) (bold if evidence for signal is seen), and 90% CL upper limit (UL, bold if no evidence) for the \( B^0 \to \omega\omega \) and \( B^0 \to \omega\phi \) decay modes.

| Mode     | \( Y_{\text{sig}} \) (events) | \( Y_{\text{sig}}^{\text{bias}} \) (events) | \( Y_{\text{peak}} \) (events) | \( Y_{\text{comb}} \) (events) | \( \epsilon \) (%) | \( \prod B_i \) (%) | \( S \) (\( \sigma \)) | \( B \) (\( 10^{-6} \)) | \( B \) UL (\( 10^{-6} \)) |
|----------|-------------------------------|---------------------------------|-----------------------------|-----------------------------|----------------|-----------------|----------------|----------------|----------------|
| \( \omega\omega \) | 69.0\( ^{+16.4}_{-15.2} \) ± 7.3 | 3810 \pm 260 | 53390 \pm 340 | 14.0 \pm 0.1 | 77.5 \pm 1.2 | 4.4 | \( 1.2 \pm 0.3 \) \( ^{+0.3}_{-0.2} \) | 1.9 |
| \( \omega\phi \) | \( ^{-2.8}_{+3.7} \) \( ^{+1.0}_{-0.0} \) | 2.9 | 473 \( ^{+84}_{-80} \) | 17730 \( ^{+160}_{-150} \) | 8.7 \pm 0.1 | 43.2 \pm 0.6 | 0.0 | \( 0.6\) \( ^{+0.3}_{-0.2} \) | 0.1 | 0.7 |

Table III also presents the measured branching fractions, total associated uncertainties, and significances. The significance, which we denote in terms of the analogous number of Gaussian standard deviations, is taken as the square root of the difference between the value of \( -2\ln L \) (with systematic uncertainties included) for zero signal events and the value at its minimum. The behavior of \( -2\ln L \) for the two modes is shown in Fig. 1. We find evidence for \( B^0 \to \omega\omega \) decays at the level of 4.4 standard deviations including systematic uncertainties. For each mode we also quote a 90% CL upper limit, taken to be the branching fraction below which lies 90% of the total of the likelihood integral in the positive branching fraction region. In calculating branching fractions we assume that the decay rates of the \( Y(4S) \) to \( B^+B^- \) and \( B^0\bar{B}^0 \) are equal \([13]\).

Figure 2 presents the data and PDFs projected onto \( m_{ES} \) and \( \Delta E \), for subsamples enriched with signal events via a set of selection criteria on the analysis variables. The selection criteria are \( |m_\omega - m_\omega^{\text{nominal}}| < 15 \text{ MeV} \), \( |m_\phi - m_\phi^{\text{nominal}}| < 8 \text{ MeV} \), \( F < 0.1 \), \( |\cos \Phi_\omega| < 0.95 \), and \( |\cos \theta_T| < 0.8 \), with \( |\Delta E| < 30 \text{ MeV} \) for the two \( m_{ES} \) plots and \( m_{ES} > 5.274 \text{ GeV} \) for the two \( \Delta E \) plots. These criteria retain 23% (40%) of \( B^0 \to \omega\omega \) (\( B^0 \to \omega\phi \)) signal events, and in both modes reject over 99% of the background events.

In summary, we have performed searches for \( B^0 \to \omega\omega \) and \( \omega\phi \) decays. We establish the following branching

TABLE III: Estimated systematic uncertainties on the branching fractions \( B(B^0 \to \omega\omega) \) and \( B(B^0 \to \omega\phi) \). Additive and multiplicative uncertainties are independent and are combined in quadrature. Note that only the additive uncertainties are consequential in the case of the \( B^0 \to \omega\phi \) mode, as essentially zero signal is observed in that mode.

| Decay Mode | \( B^0 \to \omega\omega \) | \( B^0 \to \omega\phi \) |
|------------|----------------|----------------|
| Additive uncertainties (events): | | |
| Fit bias | 5.5 | 2.0 |
| Fit parameters | 0.5 | 0.3 |
| \( B\bar{B} \) backgrounds | <0.1 | <0.1 |
| Total additive (events) | 5.5 | 2.0 |
| Multiplicative uncertainties (%): | | |
| \( f_L \) variation | +25.3 \(-8.3 \) | +18.3 \(-48.0 \) |
| Vertex finding efficiency | +5.3 \(-0.0 \) | +25.0 \(-50.0 \) |
| Track finding efficiency | 1.0 | 1.0 |
| \( \pi^0 \) efficiency | 4.2 | 2.1 |
| Kaon identification | 4.5 |
| \( \cos \theta_T \) cut efficiency | 1.3 | 1.4 |
| Submode branching fractions | 1.6 | 1.5 |
| MC statistics | 1.0 | 1.4 |
| Total number of \( B\bar{B} \) in data | 0.6 | 0.6 |
| Total multiplicative (%) | +26.3 \(-9.7 \) | +31.5 \(-69.5 \) |
FIG. 2: Projections of $m_{ES}$ (left) and $\Delta E$ (right) for a signal-enriched sample of events passing a set of dedicated selection cuts for $B^0 \to \omega \omega$ (upper plots), and $B^0 \to \omega \phi$ (lower plots). The solid curve gives the total PDF (computed without the variable plotted), the dashed curve is the signal contribution, and the dot-dashed curve is the background contribution, which includes both combinatoric and peaking $B\pi^0$ backgrounds.

fraction and upper limit:

$$B(B^0 \to \omega \omega) = (1.2 \pm 0.3^{+0.3}_{-0.2}) \times 10^{-6} \text{ and}$$  
$$B(B^0 \to \omega \phi) < 0.7 \times 10^{-6} \text{ (90\% CL)}.$$

For the branching fraction, the first uncertainty is statistical and the second is systematic. These results provide the first evidence for $B^0 \to \omega \omega$ decays and improve the constraint on the $B^0 \to \omega \phi$ branching fraction. Our results are in agreement with theoretical estimates \[\Box\]

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