Search for the $X(1812)$ in $B^{\pm} \rightarrow K^{\pm}\omega\phi$

C. Liu,37 Z. P. Zhang,37 I. Adachi,9 H. Aihara,43 K. Arinstein,1,32 T. Aushev,19,14 A. M. Bakich,40 E. Barberio,22 A. Bay,19 V. Bhardwaj,34 A. Bozek,28 M. Bračko,21,15 T. E. Browder,8 M.-C. Chang,4 A. Chen,25 B. G. Cheon,7 I.-S. Cho,47 Y. Choi,39 J. Dalseno,9 A. Drutskoy,2 W. Dzung,12 S. Eidelman,1,32 N. Gabyshev,1,32 P. Goldenzweig,2 H. Ha,17 J. Haba,9 B.-Y. Han,17 K. Hayasaka,23 M. Hazumi,9 Y. Hoshi,12 H. J. Hyun,18 K. Inami,23 A. Ishikawa,46 R. Itoh,9 M. Iwasaki,43 Y. Iwasaki,9 D. H. Kah,18 J. H. Kang,47 P. Kapusta,28 N. Katayama,9 T. Kawasaki,30 H. O. Kim,18 Y. I. Kim,18 Y. J. Kim,6 B. R. Ko,17 S. Korpar,21,15 P. Križan,20,15 P. Krokovny,9 S.-H. Kyeong,47 J. S. Lange,5 M. J. Lee,38 S. E. Lee,1 T. Lesiak,28,3 J. Li,8 A. Limosani,22 Y. Liu,23 D. Liventsev,14 R. Louvot,19 A. Matyja,28 S. McOnie,40 H. Miyata,30 Y. Miyazaki,23 R. Mizuk,14 Y. Nagasaka,10 E. Nakano,33 M. Nakao,9 H. Nakazawa,25 Z. Natkaniec,28 S. Nishida,9 K. Nishimura,8 O. Nitoh,45 S. Ogawa,31 T. Ohshima,23 S. Okuno,16 H. Ozaki,9 P. Pakhlov,14 G. Pakhlova,14 C. W. Park,39 H. Park,18 H. K. Park,18 K. S. Park,39 R. Pestotnik,15 L. E. Piilonen,46 H. Sahoo,8 K. Sakai,30 Y. Sakai,9 O. Schneider,19 J. Schümmer,9 R. Seidl,35 A. Sekiya,24 K. Senyo,23 M. E. Sevior,22 M. Shapkin,13 C. P. Shen,8 J.-G. Shiu,27 B. Shwartz,1,32 A. Sokolov,13 S. Stanič,15 T. Sumiyoshi,44 M. Tanaka,9 G. N. Taylor,22 Y. Teramoto,33 S. Uehara,9 T. Uglow,14 Y. Unno,7 S. Uno,9 Y. Usov,1,32 G. Varner,8 K. E. Varvell,40 K. Vervink,19 C. C. Wang,27 C. H. Wang,26 P. Wang,11 X. L. Wang,11 Y. Watanabe,16 R. Wedd,22 E. Won,17 B. D. Yabsley,40 Y. Yamashita,29 M. Yamauchi,9 C. Z. Yuan,11 C. C. Zhang,11 T. Zivko,15 A. Zupanc,15 and O. Zyukova1,32
(The Belle Collaboration)

1Budker Institute of Nuclear Physics, Novosibirsk
2University of Cincinnati, Cincinnati, Ohio 45221
3T. Kościuszko Cracow University of Technology, Krakow
4Department of Physics, Fu Jen Catholic University, Taipei
5Justus-Liebig-Universität Gießen, Gießen
6The Graduate University for Advanced Studies, Hayama
7Hangang University, Seoul
8University of Hawai‘i, Honolulu, Hawai‘i 96822
9High Energy Accelerator Research Organization (KEK), Tsukuba
10Hiroshima Institute of Technology, Hiroshima
11Institute of High Energy Physics, Chinese Academy of Sciences, Beijing
12Institute of High Energy Physics, Vienna
13Institute of High Energy Physics, Protvino
14Institute for Theoretical and Experimental Physics, Moscow
15J. Stefan Institute, Ljubljana
16Kanagawa University, Yokohama
17Korea University, Seoul
18Kyungpook National University, Taegu
19École Polytechnique Fédérale de Lausanne (EPFL), Lausanne
20Faculty of Mathematics and Physics, University of Ljubljana, Ljubljana
21University of Maribor, Maribor
22University of Melbourne, School of Physics, Victoria 3010
23Nagoya University, Nagoya
24Nara Women’s University, Nara
25National Central University, Chung-li
26National United University, Miao Li
27Department of Physics, National Taiwan University, Taipei
28H. Niewodniczanski Institute of Nuclear Physics, Krakow
29Nippon Dental University, Niigata
30Niigata University, Niigata
31University of Nova Gorica, Nova Gorica
32Novosibirsk State University, Novosibirsk
33Osaka City University, Osaka
34Panjab University, Chandigarh
35RIKEN BNL Research Center, Upton, New York 11973
36Saga University, Saga
We report on a search for the $X(1812)$ state in the decay $B^\pm \to K^\pm \omega \phi$ with a data sample of $657 \times 10^6$ $B\bar{B}$ pairs collected with the Belle detector at the KEKB $e^+e^-$ collider. No significant signal is observed. An upper limit $\mathcal{B}(B^\pm \to K^\pm X(1812), X(1812) \to \omega \phi) < 3.2 \times 10^{-7}$ (90% C.L.) is determined. We also constrain the three-body decay branching fraction to be $\mathcal{B}(B^\pm \to K^\pm \omega \phi) < 1.9 \times 10^{-6}$ (90% C.L.).

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This analysis uses 605 fb$^{-1}$ of data containing 657 $\times 10^6$ $B\bar{B}$ pairs. The data was collected with the Belle detector [11] at the KEKB [12] $e^+e^-$ asymmetric-energy (3.5 GeV on 8.0 GeV) collider operating at a center-of-mass (CM) energy of the $\Upsilon(4S)$ resonance.

The Belle detector is a large-solid-angle spectrometer [11]. It consists of a silicon vertex detector (SVD), a 50-layer central drift chamber (CDC), an array of aerogel threshold Cherenkov counters (ACC), an electromagnetic calorimeter comprised of CsI(Tl) crystals located inside a superconducting solenoid that provides a 1.5 T magnetic field. An iron flux return located outside the coil is instrumented to detect $K^0_L$ mesons and to identify muons (KLM).

$B$-daughter candidates are reconstructed from the decays $\omega \to \pi^+\pi^-\pi^0, \phi \to K^+K^-$ and $\pi^0 \to \gamma\gamma$. Charged tracks are identified as pions or kaons by combining information from the CDC, ACC and TOF systems. We reduce the number of poor quality tracks by requiring that $|dz| < 0.3$ cm and $|dr| < 1.5$ cm, where $|dz|$ and $|dr|$ are the distances of closest approach of a track to the interaction point in the transverse plane and z direction (opposite to the direction of the positron beam), respectively. In addition, tracks matched with clusters in the ECL that are consistent with an electron hypothesis are rejected. We use a kaon identification likelihood ratio $R_{K,\pi} = L_K/(L_K+L_\pi)$ to discriminate $K$ and $\pi$ candidates. The requirements $R_{K,\pi} > 0.4$ for a kaon and $R_{K,\pi} < 0.6$ for a pion are used. The efficiency to identify a kaon(pion) is about 94%, while the probability that a pion(kaon) is misidentified as a kaon(pion) is about 10%. Candidate $\pi^0$ mesons are reconstructed from pairs of photons, where the energy of each photon in the laboratory frame is required to be greater than 50 MeV. We select $\pi^0$ mesons with an invariant mass in the range $0.1193 \text{ GeV}/c^2 < M(\gamma\gamma) < 0.1477 \text{ GeV}/c^2$ and a momentum in the laboratory frame $p_\pi^0 > 0.38 \text{ GeV}/c$.

Using a sample of $5.8 \times 10^7 J/\psi$ events, the BES collaboration observed a near-threshold enhancement in the $\omega \phi$ invariant mass spectrum from the double OZI suppressed $J/\psi \to \gamma\omega \phi$ decay with a statistical significance of more than $10\sigma$ [3]. When fitted with a Breit-Wigner, this enhancement, called $X(1812)$, has the following mass, width, and product of branching fractions:

$$M = (1812^{+19}_{-26} \pm 18) \text{ MeV}/c^2,$$

$$\Gamma = (105 \pm 20 \pm 28) \text{ MeV}/c^2,$$

$$\mathcal{B}(J/\psi \to \gamma X, X \to \omega \phi) = (2.60 \pm 0.27 \pm 0.65) \times 10^{-4}.$$}

Partial wave analysis favors a spin-parity assignment of $J^{PC} = 0^{++}$ for the $X(1812)$. In the related $\omega \phi$ mode, Belle has seen a dramatic threshold enhancement in $B^+ \to K^+ \omega \phi$, the $\Upsilon(3940)$ [2], which has now been confirmed by BaBar [3].

If the $X(1812)$ is a $q\bar{q}$ meson, the $X(1812) \to \omega \phi$ branching fraction should be very small due to OZI suppression and the limited available phase space, in contrast with the BES observation. Suggestions have been made that the $X(1812)$ may be a tetraquark state (with structure $Q^2\bar{Q}^2$), since some tetraquark states decay to vector-vector mesons dominantly by “falling apart” and their masses are at the threshold of two vector mesons [3]. Other works speculate that it may be a hybrid [3], glueball state [4], an effect due to intermediate meson rescatterings [3] or a threshold cusp attracting a resonance [5]. In this paper, we report our search for this state in the decay $B^\pm \to K^\pm \omega \phi$. On the other hand, this decay proceeds via a $b \to s$ penguin with $s\bar{s}$ and $u\bar{u}$ popping. A similar decay mode $B^+ \to K^+ \phi \phi$, which proceeds via a $b \to s$ penguin diagram with double $s\bar{s}$ popping, is the only observed charmless $B \to VVV$ (two vector mesons and one pseudoscalar meson) mode and has a rather large branching fraction $[4.9^{+2.4}_{-2.2}] \times 10^{-6}$ [3, 10]. Therefore, even if the $X(1812)$ cannot be observed, measurement of the $B^\pm \to K^\pm \omega \phi$ three-body decay is also helpful for investigating decay mechanisms.

$37$ University of Science and Technology of China, Hefei
$38$ Seoul National University, Seoul
$39$ Sungkyunkwan University, Suwon
$40$ University of Sydney, Sydney, New South Wales
$41$ Toho University, Funabashi
$42$ Tohoku Gakuin University, Tagajo
$43$ Department of Physics, University of Tokyo, Tokyo
$44$ Tokyo Metropolitan University, Tokyo
$45$ Tokyo University of Agriculture and Technology, Tokyo
$46$ IPNAS, Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061
$47$ Yonsei University, Seoul
Particles satisfying the above selection criteria are then used to reconstruct $\omega$ and $\phi$ mesons. We select candidates in the invariant mass windows 0.75 GeV/$c^2 < M_{\pi^+\pi^-\pi^0} < 0.81$ GeV/$c^2$ and $1.00$ GeV/$c^2 < M_{K^+K^-} < 1.04$ GeV/$c^2$. A vertex fit for the $\phi$ and $\omega$ candidates is also performed. In addition, we require three kaons in the final state, one directly from the $B$-meson decay and the other two from the $\phi$ decay. To distinguish the two kinds of kaons and reduce multiple candidates, we require kaons from the $\phi$ to have momenta $p_{K^\pm} < 1.5$ GeV/$c$ in the CM frame.

Candidate $B^{\pm} \rightarrow K^{\pm}\omega\phi$ decays are identified by using the energy difference ($\Delta E$) and the beam-energy-constrained mass ($M_{bc}$). These are defined as $\Delta E \equiv E_B - E_{\text{beam}}$ and $M_{bc} \equiv \sqrt{E_{\text{beam}}^2 - p_B^2}$, where $E_{\text{beam}}$ denotes the beam energy, $E_B$ and $p_B$ denote the reconstructed energy and momentum of the candidate $B$-meson, all evaluated in the $e^+e^-$ CM frame. We select events satisfying $|\Delta E| < 0.2$ GeV and $5.20$ GeV/$c^2 < M_{bc} < 5.29$ GeV/$c^2$, and define signal regions $-0.15$ GeV $< \Delta E < 0.05$ GeV and $5.27$ GeV/$c^2 < M_{bc} < 5.29$ GeV/$c^2$.

The dominant source of background arises from random combinations of particles in continuum $e^+e^- \rightarrow q\bar{q}$ events ($q=u,d,s,c$). To discriminate spherical $BB$ events from jet-like $q\bar{q}$ events, we use event-shape variables: specifically, 16 modified Fox-Wolfram moments [13] combined into a Fisher discriminant, $F$ [14]. Additional discrimination is provided by $\theta_B$, the polar angle in the CM frame between the $B$ direction and $z$ direction. Correctly reconstructed $B$-mesons follow a $(1 - \cos^2 \theta_B)$ distribution, while fake candidates from continuum tend to be uniform in $\cos \theta_B$.

Further continuum background suppression is achieved using $b$-flavor tagging information. The Belle flavor tagging algorithm [14] yields the flavor of the tagged meson, $q(=\pm 1)$, and a flavor-tagging quality factor, $r$. The latter ranges from zero for no flavor discrimination to one for unambiguous flavor assignment. For signal events, $q$ is usually consistent with the flavor opposite to that of the signal $B$, while it is random for continuum events. Thus, the quantity $q \tau F_B$ is used to separate signal and continuum events, where $F_B$ is the charge of the signal $B$: $F_B = \pm 1$ ($-1$) for $B^{+}$ ($B^{-}$)

We use a Monte Carlo (MC) sample [14] to form $F$ and to obtain the $\cos \theta_B$ and $q \tau F_B$ distributions. Probability density functions (PDFs) are derived from $F$ and the $q \tau F_B$ distributions and are multiplied to form signal ($L_s$) and continuum background ($L_{bg}$) likelihood functions, which are further combined to form a likelihood ratio $R_{s} = L_{s}/(L_{s} + L_{bg})$. We divide events into six $q \tau F_B$ bins and determine the optimal $R_{s}$ selection criteria for each bin by maximizing $N_s/\sqrt{N_s + N_{bg}}$, where $N_s$ is the number of signal MC events in the signal region, and $N_{bg}$ is the number of background events estimated to be in the signal region by assuming $B(B^{\pm} \rightarrow K^{\pm}\omega\phi) = 1.0 \times 10^{-3}$.

This optimization preserves 57.9% of the signal while rejecting 98.6% of the continuum background.

Applying all of the above criteria, the fraction of events having multiple candidates is 21%. To select the $B$-meson candidate, we add the $\chi^2$ of the $\omega$ meson vertex fit, and the $\chi^2$ of a $\pi^0 \rightarrow \gamma\gamma$ fit constrained to the PDG value of $\pi^0$ mass: the candidate with the smallest value is chosen. If multiple $B$ candidates still remain, we use the $\chi^2$ of the $\phi$ meson vertex fit and $\chi^2$ of the $B$-meson vertex fit to choose the best one.

![Graph](image-url)

**FIG. 1:** Projection of the data (points with error bars) and fit results onto (a) $M_{bc}$, (b) $\Delta E$, (c) $M_{s+\pi^-\pi^0}$, (d) $M_{K+K^-}$ with the other variables satisfying $M_{bc} \in (5.27,5.29)$ GeV/$c^2$, $\Delta E \in (0.15,0.05)$ GeV, $M_{s+\pi^-\pi^0} \in (0.75,0.81)$ GeV/$c^2$, $M_{K+K^-} \in (1.00,1.04)$ GeV/$c^2$ : signal (dot-dashed), $q\bar{q}$ (dashed), $BB$ (dot-dot-dashed) and total (solid).

In addition to the dominant continuum background, charmless $B$ decay ($b \rightarrow c$) and charmless $B$ decay ($b \rightarrow u,d,s$) backgrounds are studied using dedicated MC samples that are respectively about two and 25 times the size of the data sample. Charmless $B$ decay background is found to be small and is neglected. The following charm decay channels are studied using dedicated Monte Carlo samples: $B^{+} \rightarrow D^{+}\pi^0\pi^+K^\pm$, $D_{s}^{+} \rightarrow \pi^+\pi^0K^\pm$, $D_{s}^{+} \rightarrow \pi^+\phi$; $B^{+} \rightarrow D^{+}\pi^+K^\pm$, $D_{s}^{+} \rightarrow \pi^0\pi^+\phi$ and $B^{+} \rightarrow D^{0}/D^{+}K^{+}$, $D_{s}^{0}/D^{+}\rightarrow \pi^+\pi^-\pi^0K^+K^-$. To measure the three-body $B^+ \rightarrow K^+\omega\phi$ branching fraction, we require $M_{K+K^-} < 0.15$ GeV/$c^2$ as well as $M_{\pi^0K^+K^-} > 0.15$ GeV/$c^2$, where $m_{D_s}$ is the nominal $D_s$ mass [14], to veto the $D_s$ background.

We obtain the signal yield using a four-dimensional extended unbinned maximum likelihood (ML) fit to $\Delta E$, $M_{bc}$, $M_{\pi\pi}$ and $M_{KK}$. The likelihood function consists of the following components: signal decays, continuum
and thus the yield is fixed in the fit according to MC. The signal $M_{bc}$ is parameterized by the sum of a single Gaussian and an ARGUS function \cite{18}, $\Delta E$ by a Gaussian and a Crystal Ball function \cite{19}, and $M_{K+K}$, $M_{\pi^+\pi^-\pi^0}$ by Breit-Wigner functions. For continuum background, $M_{bc}$ is parameterized by an ARGUS function, $\Delta E$ by a second-order Chebyshev polynomial, and $M_{K+K}$, $M_{\pi^+\pi^-\pi^0}$ by the sum of Breit-Wigner functions and first-order Chebyshev polynomials. $\bar{B}B$ background modelling is similar, but with a first-order Chebyshev for $\Delta E$ and for $M_{\pi^+\pi^-\pi^0}$. All function parameters are determined from MC simulation.

In our final fit to the data, the signal and $q\bar{q}$ yields are allowed to vary; the fraction of $b \to c$ events is very small and thus the yield is fixed in the fit according to MC.

The likelihood function to be maximized is given by

$$L = \frac{e^{-(\sum_j Y_j)}}{N!} \prod_{j=1}^{N} (Y_j P_j)$$

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

Figure 1 shows the fit results. Peaking behavior observed in $\Delta E$, $M_{bc}$, $M_{\pi\pi}$ and $M_{KK}$ is consistent with that from MC expectations. The branching fraction is evaluated using the following quantities: the signal yield $Y_{\omega\phi K} = 22.1^{+8.3}_{-7.2}$ with reconstruction efficiency $\varepsilon = 7.04 \times 10^{-2}$; the combined daughter branching fraction $B_d = 0.439$ \cite{17}; a correction of 0.946 to the efficiency of $K/\pi$ identification requirements, which takes into account small differences between MC and data; and a total of $657 \times 10^6$ produced $\bar{B}B$ pairs, where equal fractions of $\bar{B}^+B^-$ and $B^0\bar{B}^0$ are assumed.

The sources of systematic error are listed in Table I. The quoted 6\% track reconstruction efficiency is from the consideration that there are five tracks in a selected event and for each track the efficiency error is 1.2\%. The errors due to continuum suppression requirements are obtained by varying these cuts while the errors on the PDF shapes are obtained by varying all fixed parameters by $\pm 1\sigma$. Toy MC tests and GEANT-based Detector Simulation (GISM) tests are performed, we find that the fit bias can be neglected. To estimate the error due to the $b \to c$ contribution, we vary the normalizations by $\pm 50\%$.

Our final result for the three-body branching fraction based on the 605 fb$^{-1}$ data sample is

$$B(B^\pm \to K^\pm \omega\phi) = (1.15^{+0.43+0.14}_{-0.38-0.13}) \times 10^{-6},$$

where the first error quoted is statistical and the second systematic. We obtain the 90\% confidence level upper limit $B(B^\pm \to K^\pm \omega\phi) < 1.9 \times 10^{-6}$ by a frequentist method using ensembles of pseudo-experiments. For a given signal yield, 10000 sets of signal and background events are generated according to the PDFs, and fits are performed. The confidence level is obtained from the fraction of samples that give a fit yield larger than that of data (22.1). We take into account systematic errors by varying the fit yield by the total systematic errors described in Table I. The significance of the signal, estimated using this method, is 2.8\sigma.

![Image](FIG. 2: Mass spectrum in the $\omega\phi$ fit with the following components: $B^+ \to K\omega\phi$ three-body (dotted), $\bar{B}B$ (dot-dashed), $q\bar{q}$ (dashed), $D^0$ (dot-dot-dashed), $D_s$ (dot-dot-dot-dashed), $B^+ \to K^+X(1812)$ (long-dashed), and total(solid). The spectrum is also shown in the inset with an expanded vertical scale.)

We next study the $\omega\phi$ mass spectrum. Because the aforementioned $M_{K+K} - m_{D_s}$ and $|M_{\pi^+\pi^-\pi^0} - m_{D_s}|$ mass cuts influence the shape of the $\omega\phi$ invariant mass spectrum, we did not use them and fit the $D^0$ and $D_s$ backgrounds simultaneously.

We produced 0.6 million (2.0 million) $D^0$ ($D_s$) background MC events for the decay $B^\pm \to K^\pm X(1812), X(1812) \to \omega\phi$. The $X(1812)$ mass and width are taken from the BES measurement and its

| Type                      | Fractional error (%) |
|----------------------------|----------------------|
|                            | $+\sigma$            | $-\sigma$            |
| Tracking                   | 6.00                 | 6.00                 |
| $K/\pi$ ID                 | 2.90                 | 2.90                 |
| $\pi^+$ Reconstruction     | 4.00                 | 4.00                 |
| Daughter $B$               | 1.45                 | 1.45                 |
| Signal/Background Modeling | 5.25(31.1)           | 2.50(22.7)           |
| $\bar{B}B$ Background Yield| 1.75(2.10)           | 0.89(1.60)           |
| MC Statistics              | 0.56(1.06)           | 0.56(1.06)           |
| Continuum Suppression      | 7.21(12.0)           | 7.26(12.4)           |
| $N_{\omega\phi}$           | 1.36(1.36)           | 1.36(1.36)           |
| Total                      | 12.1(34.4)           | 11.2(27.1)           |
PDF is modeled by an rARGUS (reversed ARGUS) function, \( F_{\text{rARGUS}}(x) = F_{\text{ARGUS}}(2t - x) \), where \( t \) is the threshold. The three-body decay PDF is the sum of an rARGUS function and a Breit-Wigner with a threshold. The background PDF is modeled by an rARGUS (reversed ARGUS) function and a Gaussian, while the background PDF is also modeled by rARGUS functions. We obtained all the parameters from MC samples. In our final fit to the data, we fixed the yield of \( D^0 \) and \( D_s \) backgrounds according to the PDG branching fractions, and fixed the yield of \( B\bar{B} \) background according to MC simulation.

The final result is shown in Fig. 2. No significant signal is observed; the yield of \( X(1812) \) is \( 0.27 \pm 0.3 \text{ pb}^{-1} \) events. The systematic errors are also listed in Table I, where those in parentheses are for the items that differ from those in the three-body decay analysis. We also include the errors from the fraction of \( D^0 \), \( D_s \) background and the \( X(1812) \) width into signal/background modeling. Using the pseudo-experiment method described above and taking the systematic errors into account, we find a limit on the product branching fraction of \( B(B^\pm \to K^\pm X(1812), X(1812) \to \omega \phi) < 3.2 \times 10^{-7} \) (90% C.L.).

In summary, using a data sample of 605 fb\(^{-1} \) collected with the Belle detector, we present a search for the \( X(1812) \) meson in the decay \( B^\pm \to K^\pm \omega \phi \). No significant signal is observed. An upper limit for the product \( B(B^\pm \to K^\pm X(1812), X(1812) \to \omega \phi) < 3.2 \times 10^{-7} \) (90% C.L.) is determined. We also measure the three-body \( B^\pm \to K^\pm \omega \phi \) decay branching fraction \( B(B^\pm \to K^\pm \omega \phi) = [1.15_{-0.38}^{+0.43} +0.14(-1.9)] \times 10^{-6} \), where the upper limit is at the 90% confidence level.

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