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(Dated: April 17, 2018)
Using $1.31 \times 10^9 \ J/\psi$ events collected by the BESIII detector at the BEPCII $e^+e^-$ collider, we report the first observation of the $h_1(1380)$ in $J/\psi \to \eta' h_1(1380)$ with a significance of more than ten standard deviations. The mass and width of the possible axial-vector strangeonium candidate $h_1(1380)$ are measured to be $M = (1423.2 \pm 2.1 \pm 7.3) \text{ MeV}/c^2$ and $\Gamma = (90.3 \pm 9.8 \pm 17.5) \text{ MeV}$. The product branching fractions, assuming no interference, are determined to be $B(J/\psi \to \eta' h_1(1380)) \times B(h_1(1380) \to K^+(892)^+K^- + \text{c.c.}) = (1.51 \pm 0.09 \pm 0.21) \times 10^{-4}$ and $B(J/\psi \to \eta' h_1(1380)) \times B(h_1(1380) \to K^+(892)K^+ + \text{c.c.}) = (2.16 \pm 0.12 \pm 0.29) \times 10^{-4}$. The first uncertainties are statistical and the second are systematic. Isospin symmetry violation is observed in the decays $h_1(1380) \to K^+(892)^+K^- + \text{c.c.}$ and $h_1(1380) \to K^+(892)^0K^0 + \text{c.c.}$. Based on the measured $h_1(1380)$ mass, the mixing angle between the states $h_1(1170)$ and $h_1(1380)$ is determined to be $(35.9 \pm 2.6)^\circ$, consistent with theoretical expectations.

The strangeonium spectrum is less well known at present compared to the charmonium and bottomonium spectra. Judging from its mass and large decay width to $K^+(892)K^+ + \text{c.c.}$, the $h_1(1380)$ is a possible candidate for the $s\bar{s}$ partner of the $J^{PC} = 1^{++}$ axial-vector state $h_1(1170)$. Experimentally, the state $h_1(1380)$ has been observed by both the LASS [2] and Crystal Barrel [3] collaborations, with masses and widths measured to be $M = (1380 \pm 20) \text{ MeV}/c^2$, $\Gamma = (80 \pm 30) \text{ MeV}$ by LASS and $M = (1440 \pm 60) \text{ MeV}/c^2$, $\Gamma = (170 \pm 80) \text{ MeV}$ by Crystal Barrel. Theoretically, the mass of the strangeonium $h_1(1380)$ is predicted to be $M = 1468 \text{ MeV}/c^2$ according to meson-mixing models [4, 5], or $M = 1386.42 \text{ MeV}/c^2$, 1470 MeV/c$^2$, (1499 $\pm$ 16) MeV/c$^2$ or 1511 MeV/c$^2$ according to quark models [6, 7]. Assuming the $h_1(1380)$ is the $s\bar{s}$ partner of the $1^P_1$ state $h_1(1170)$, the $h_1(1380)-h_1(1170)$ mixing angle $\alpha_{h_1}$ can be determined from the masses of the $h_1(1380)$, $h_1(1170)$, $h_1(1235)$, $K_1(1400)$ and $K_1(1270)$, and the mixing angle between the $K_1(1400)$ and $K_1(1270)$ ($\theta_{K_1}$) [11]. Once the mixing angle is determined, it may shed light on the quark content of the $h_1(1380)$. In order to better understand the nature of the $h_1(1380)$, improved measurements are crucial.

With the huge charmonium data sets collected by the BESIII experiment, the strangeonium spectrum can be studied in charmonium decays. BESIII previously measured the mass and width of the $h_1(1380)$ as $M = (1412 \pm 9) \text{ MeV}/c^2$ and $\Gamma = (84 \pm 24) \text{ MeV}$ via $\psi(3686) \to \gamma \chi_{cJ}(J=1,2), \chi_{cJ}(J=1,2) \to \phi h_1(1380)$ and $h_1(1380) \to K^+(892)K^-$, with a $1.06 \times 10^8 \psi(3686)$ events collected at BESIII [12]. These results are consistent with those from the LASS and Crystal Barrel experiments [2, 3], but are limited by the low statistics of the $\chi_{cJ}$ samples and large uncertainties from the interference of $h_1(1380)$ with the intermediate states $\phi(1680)$ and $\phi(1850)$. A more precise measurement would be useful for improving the understanding of the mass, quark content and corresponding mixing angle for the $h_1(1380)$.

In this paper, we present the first observation of $J/\psi \to \eta' h_1(1380)$, where $h_1(1380) \to K^+(892)K^- + \text{c.c.}$, $K^+K^-\pi^0 K^0 K^\pm \pi^\mp$, using a sample of $1.31 \times 10^9 J/\psi$ events [13, 14].

The BESIII detector [15] is a magnetic spectrometer operating at BEPCII, a double-ring $e^+e^-$ collider with center of mass energies between 2.0 and 4.6 GeV. The cylindrical BESIII detector has an effective geometrical acceptance of 93% of 4$\pi$. It is composed of a small cell helium-based main drift chamber (MDC) which provides momentum measurements for charged particles, a time-of-flight system (TOF) based on plastic scintillators that is used to identify charged particles, an electromagnetic calorimeter (EMC) made of CsI(Tl) crystals used to measure the energies of photons and electrons, and a muon system (MUC) made of resistive plate chambers (RPC). The momentum resolution of the charged particles is 0.5% at 1 GeV/c in a 1 Tesla magnetic field. The energy loss ($dE/dx$) measurement provided by the MDC has a resolution of 6%, and the time resolution of the TOF is 80 ps (110 ps) in the barrel (end caps). The photon energy resolution is 2.5% (5%) at 1 GeV in the barrel (end caps) of the EMC.

A GEANT4 based [16] simulation software BOOST [17] is used to simulate the Monte Carlo (MC) samples. An inclusive $J/\psi$ MC sample is generated to estimate the backgrounds. The production of the $J/\psi$ resonance is simulated by the MC event generator KKMC [18], while the decays are generated by BESevtgen [19] for known decays modes with branching fractions according to the world average values [1], and by the Lundcharm model [20] for the remaining unknown decays. Exclusive MC samples are generated to determine the detection efficiencies of the signal processes and optimize event selection criteria.

For $J/\psi \to \eta' K^+ K^- \pi^0$ with $\eta' \to \pi^+ \pi^- \eta$, $\eta \to \gamma \gamma$, and $\pi^0 \to \gamma \gamma$, candidate events are required to have four charged tracks with zero net charge and at least four photons. Each charged track is required to be within $0.0<\cos \theta<0.93$ and must pass with-in 10 cm (1 cm) of the interaction point in the beam (radial) direction. Information from TOF and $dE/dx$ measurements is combined to form particle identification (PID) confidence levels for the $\pi$, $K$, and $p$ hypotheses, respectively. Each track is assigned the particle type corresponding to the hypothesis with the highest confidence level. Two oppositely charged kaons and pions are required for each event. Photon candidates are reconstructed from isolated clusters of energy deposits in the EMC and must have an energy of at least 25 MeV for barrel showers ($|\cos \theta|<0.8$), or 50 MeV for end cap showers ($0.86<|\cos \theta|<0.92$). The energy deposited
in nearby TOF counters is also included. EMC cluster timing requirements (0 ≤ t ≤ 14 in units of 50 ns) are used to suppress electronics noise and energy deposits unrelated to the event.

To improve the momentum and energy resolution and suppress background events, a four-constraint (4C) kinematic fit imposing energy-momentum conservation is performed under the hypothesis $J/\psi \rightarrow \gamma\gamma\gamma\gamma\pi^+\pi^-K^+K^-$, and a requirement of $\chi^2_{4C} < 100$ is imposed. For events with more than four photon candidates, the combination with the smallest $\chi^2_{4C}$ is retained. Photon pairs corresponding to the best $\pi^0\eta$, $\pi^0\eta'$ and $\eta\eta$ candidates are selected separately by choosing the combination that with $\chi^2_{4C} = (M_{\gamma\gamma} - m_\gamma)^2/\sigma_{\gamma\gamma}^2 + (M_{\gamma\gamma} - m_\gamma)^2/\sigma_{\gamma\gamma}^2$, where $a\beta = \pi^0\eta$, $\pi^0\eta'$, or $\eta\eta$ and each mass resolution $\sigma_{a\beta}$ is obtained from the MC simulation. Only the combination with $\chi^2_{4C} < \chi^2_{4\pi\eta}$ and $\chi^2_{4C} < \chi^2_{4\eta'}$ is retained. The $\pi^0$ and $\eta$ candidates are selected by requiring $|M(\gamma\gamma) - m_{\gamma\gamma}| < 0.02$ GeV/c$^2$ and $|M(\gamma\gamma) - m_{\gamma\gamma}| < 0.03$ GeV/c^2, respectively. The $\pi^0\eta$ invariant mass distribution for the selected events is shown in Fig. 1 where an $\eta'$ peak is evident. The peak around 1.3 GeV/c^2 is due to $f_2(1285)$ or $\eta(1295)$ decays. Events with $|M(\pi^+\pi^-\eta) - m_{\eta'}| < 0.03$ GeV/c^2 are selected for further analysis. Here, $m_{\pi^0}, m_{\eta},$ and $m_{\eta'}$ are the nominal masses of $\pi^0$, $\eta$, and $\eta'$.

![FIG. 1. Distribution of the $\pi^+\pi^-\eta$ invariant mass in the $\eta'K^+K^-$ mode. The dots with error bars are data and the histogram is the inclusive MC sample.](image)

After the above selection criteria, the distribution of the invariant mass of $K^+\pi^0$ versus that of $K^-\pi^0$ found in data is shown in Fig. 2(a). Bands for the $K^*+(892)^\pm$ are evident, indicating that the $J/\psi \rightarrow \eta'K^*+(892)^+K^-$ mode, a process is dominant. Figures 2(b) and (c) show the projections of the $K^+\pi^0$ and $K^-\pi^0$ invariant masses, respectively.

For $J/\psi \rightarrow \eta'K^0_SK^+\pi^-$ with $\eta' \rightarrow \pi^+\pi^-\eta$, $\eta \rightarrow \gamma\gamma$ and $K^0_S \rightarrow \pi^+\pi^-$, candidate events are required to have six charged tracks with zero net charge and at least two photons. Each charged track and photon candidate is reconstructed as described above except for the $\pi^+\pi^-$ pair from $K^0_S$. The $K^0_S$ candidates are reconstructed from all combinations of pairs of oppositely charged tracks, assuming each of the two tracks is a pion. A secondary vertex fit is performed and the fit $\chi^2$ is required to be less than 100. If more than one $K^0_S$ candidate is reconstructed in an event, the one with the minimum $|M(\pi^+\pi^-) - m_{K^0_S}|$ is selected for further analysis. The $K^0_S$ candidates are further required to satisfy $|M(\pi^+\pi^-) - m_{K^0_S}| < 0.01$ GeV/c^2. Here, $m_{K^0_S}$ is the nominal mass of $K^0_S$. The other four charged tracks must be identified as three pions and one kaon according to PID information.

For each event, a 4C kinematic fit is performed under the hypothesis $J/\psi \rightarrow \gamma\gamma\pi^+\pi^-K^-\pi^+\pi^-$, where the $K^0_S$ candidate is included with the parameters obtained from the second vertex fit. A requirement of $\chi^2_{4C} < 100$ is imposed. The $\eta$ candidate is selected by requiring $|M(\gamma\gamma) - m_{\gamma\gamma}| < 0.03$ GeV/c^2, and the $\eta'$ signal is observed and selected with the requirement of $|M(\pi^+\pi^-\eta) - m_{\eta'}| < 0.03$ GeV/c^2. The $\pi^+\pi^-\eta$ mass distribution is shown in Fig. 3. Clear bands and peaks for $K^*(892)^\pm$ and $K^*(892)^0/K^*(892)^0$ are visible in Fig. 4.

To determine the signal yields, a simultaneous unbinned maximum likelihood fit is performed to the $M(K^+\pi^0)$ and $M(K^-\pi^0)$ spectra for the $K^+K^-\pi^0$ mode. The signal shapes are taken directly from the corresponding MC simulation. The backgrounds are described with fifth-order Chebychev polynomial functions.

In the $K^+K^-\pi^0$ mode, the efficiencies of the charged conjugated channels are found to be consistent within the statistics uncertainties, and the number of signal events containing a $K^*(892)^+$ or a $K^*(892)^-$ is constrained to be the same in the fit. The fit yields a total of 5066 ± 79 events, as shown in Fig. 2. In the $K^0_SK^+\pi^0$ mode, a similar simultaneous fit is performed to the $M(K^0_S\pi^\pm)$ and $M(K^0_S\pi^\mp)$ spectra. The fit results are of similar quality compared to those in Figs. 2(b) and (c) and yield $7749 \pm 134$ $K^*(892)^\pm$ and $8268 \pm 137$ $K^*(892)^0$ or $K^*(892)^0$ events. Here, the uncertainties are statistical only.

The branching fractions are calculated with $B(J/\psi \rightarrow \eta'K^+K^- c.c.) = N_{\text{obs}}^\text{et} \times (N_{J/\psi} \times B \times \epsilon)$, where $N_{\text{obs}}^\text{et}$ is the total number of signal events, $N_{J/\psi}$ is the number of $J/\psi$ decays [13, 14]; $\epsilon$ is the selection efficiency obtained from a phase space MC simulation; and $B$ is the product of branching fractions of intermediate states. Considering the negligible differences for the final states with and without the $h_1(1380)$, the signal efficiencies are obtained using exclusive MC samples without the $h_1(1380)$. The selection efficiencies are 9.3% and 10.3% (9.8%) for the decay modes $\eta'K^+K^-\pi^0$ and $\eta'K^0_SK^+\pi^-$ with an intermediate $K^*(892)^\pm$ ($K^*(892)^0/K^*(892)^0$), respectively.

The measured branching fractions are $B(J/\psi \rightarrow \eta'K^*+(892)^+K^- + c.c.) = (1.50 \pm 0.02) \times 10^{-3}$ for the $\eta'K^+K^-\pi^0$ mode and $B(J/\psi \rightarrow \eta'K^*+(892)^0K^- + c.c.) = (1.47 \pm 0.03) \times 10^{-3}$, $B(J/\psi \rightarrow \eta'K^*+(892)^0K^0 + c.c.) = (1.66 \pm 0.03) \times 10^{-3}$ for the $\eta'K^0_SK^+\pi^-$ mode. Here, the uncertainties are statistical only.

Intermediate states are studied by examining the $K\bar{K}\pi$ invariant mass distributions. The $K^*(892)$ signals are
Data

Kampled by a phase space factor Breit-Wigner function with a mass-dependent width multiplied by a phase space factor. Assuming that this threshold enhancement signal shape is parameterized using a relativistic S-wave Breit-Wigner function with a mass-dependent width multiplied by a phase space factor $q$,

$$\left| \frac{\sqrt{m\Gamma(m)}}{m^2 - m_0^2 + im\Gamma(m)} \right|^2 \times q \quad (1)$$

where $\Gamma(m) = \Gamma_0 (\frac{m}{m_0})^{2l+1}$, $l = 0$ is the orbital momentum, $m$ is the reconstructed mass of $K^*(892)\bar{K}$, $m_0$ and $\Gamma_0$ are the nominal resonance mass and width, $q$ is the $q^0$ momentum in the $J/\psi$ rest frame, $p$ is the $K^*$ momentum in the rest frame of the $K^*(892)\bar{K}$ system, and $m_0$ is the $K^*$ momentum in the resonance rest frame at $m = m_0$. The large total decay widths of the $K^*(892)$ are taken into account by convolving the momentum of the $K^*$ with the invariant mass distribution of the $K^*(892)$. The mass resolution, fixed at the MC simulated value of 6.0 MeV/c^2, is taken into account by convolving the signal shape with a Gaussian function. In the fit, the background shape is fixed to that from inclusive MC and its magnitude is allowed to vary. The possible interference between the signal and background is neglected in the fit.

The fit yields a mass of $(1423.2 \pm 2.1)$ MeV/c^2 and a width of $(90.3 \pm 9.8)$ MeV, as shown in Fig. 4. The fit qualities ($\chi^2$/ndf, with ndf = 6) are 1.41 for the $K^+\bar{K}^0\pi^0$ and 1.09 for the $K^0\bar{K}^0\pi^0$ modes. The numbers of the fitted $h_1(1380)$ signal events are 1054 ± 60 and 1195 ± 68 for the $K^+\bar{K}^0\pi^0$ and $K^0\bar{K}^0\pi^0$ modes, respectively. The product branching fractions are

$$B(J/\psi \rightarrow \eta' h_1(1380)) \times B(h_1(1380) \rightarrow K^*(892)K^+) \times c.c.) = (1.51 \pm 0.09) \times 10^{-4}$$

in the $\eta'K^+\bar{K}^0\pi^0$ mode and

$$B(J/\psi \rightarrow \eta' h_1(1380)) \times B(h_1(1380) \rightarrow K^*(892)\bar{K}) \times c.c.) = (2.16 \pm 0.12) \times 10^{-4}$$

in the $K^0\bar{K}^0\pi^0$ mode. Here, the uncertainties are statistical only. The statistical significance is calculated by comparing the fit likelihoods with and without the $h_1(1380)$ signal with the change on the number of degrees of freedom considered. The differences due to the fit uncertainties by changing the fit range, the signal shape, or the background shape are included into the systematic uncertainties. In all cases, the significance is found to be larger than 10σ. According to isospin symmetry, $B(h_1(1380) \rightarrow K^*(892)K^- + c.c.)$ should be equal to $B(h_1(1380) \rightarrow K^*(892)K^0 + c.c.)$. However, considering the mass differences between the charged and neutral $K$ and $K^*(892)$ mesons ($\Delta m_K = 3.97$ MeV/c^2, and $\Delta m_{K^*(892)} = 4.15$ MeV/c^2) and the fact that the $h_1(1380)$ state resides near the $K^*(892)\bar{K}$ threshold,

FIG. 2. (a) Scatter plot of the $K^+\pi^0$ invariant mass versus that of $K^-\pi^0$ in selected data events. Fits to the (b) $M(K^+\pi^0)$ and (c) $M(K^-\pi^0)$ distributions, where the dots with error bars are data, the solid curves are the total fit results, the dashed curves indicate backgrounds and the dotted-dashed curves are $K^*(892)$ signal shapes.

FIG. 3. Distribution of the $\pi^+\pi^-\eta$ invariant mass closest to the $\eta^*$ mass in the $\eta^*K^0\bar{K}^0\pi^0$ mode. The dots with error bars are data and the histogram is the inclusive MC sample.

selected using $|M(K^\pm\pi^0) - m_{K^*(892)\pm}| < 0.15$ GeV/c^2 in the $\eta^*K^+\bar{K}^-\pi^0$ mode and $|M(K^0\bar{K}^\mp\pi^0) - m_{K^*(892)\mp}| < 0.15$ GeV/c^2 or $|M(K^\mp\pi^\mp) - m_{K^*(892)0}| < 0.15$ GeV/c^2 in the $\eta^*K^0\bar{K}^0\pi^0$ mode. Here, $m_{K^*(892)\pm}$ and $m_{K^*(892)0}$ are the nominal masses of $K^*(892)\pm$ and $K^*(892)0$.

Figure 3 shows the selected $K^+\bar{K}^-\pi^0$ and $K^0\bar{K}^0\pi^0$ invariant mass distributions after the $K^*(892)$ selection, where a distinct peak near the $K^*(892)\bar{K}$ mass threshold is observed. Assuming that this threshold enhancement comes from an intermediate state and taking into account its mass, its decays through $K^*(892)\bar{K}$, and charge parity conservation, the most likely assignment for this structure is the $h_1(1380)$ ($J^{PC} = 1^{--}$).

To characterize the observed enhancement and determine the signal yields, a simultaneous unbinned maximum likelihood fit is performed to the $M(K^*(892)\bar{K})$ distributions in the $K^+\bar{K}^-\pi^0$ and $K^0\bar{K}^0\pi^0$ modes with a common mass and width for the $h_1(1380)$ signal. The signal shape is parameterized using a relativistic $S$-wave Breit-Wigner function with a mass-dependent width multiplied by a phase space factor $q$. The confidence levels are calculated for the mass and width of the $h_1(1380)$ signal.
isospin symmetry breaking effects are expected [22, 23].

We also fit the $K^{+}(892)\bar{K}$ invariant mass distribution allowing interference between the $h_1(1380)$ signal and the non-resonant background. The phase angle is allowed to be free, and the lowest negative likelihood corresponds to constructive interference. The final fit and the individual contribution of each component are shown in Fig. 6. The fitted mass and width of the $h_1(1380)$ are $M = (1441.7 \pm 4.9)$ MeV/$c^2$ and $\Gamma = (111.5 \pm 12.8)$ MeV. In this analysis, the fit results without considering interference are taken as the nominal values.

Sources of systematic uncertainties for the $h_1(1380)$ resonance parameters include the mass calibration, parameterizations of the signal and background shapes, fit range and mass resolution. The uncertainty from the mass calibration is estimated using the difference between the measured $\eta'$ mass and the nominal value [1]. The uncertainty due to the mass resolution is estimated by varying the resolution, which is determined from the MC simulation. For the systematic uncertainty associated with the signal shape, an alternative fit is performed by assuming a $P$-wave between the $\eta'$ and the $h_1(1380)$. The uncertainty due to the background shape is determined by changing the inclusive MC shape to a third-order polynomial function. The fit range is varied to determine the associated uncertainty. Finally the individual uncertainties are summarized in Table I. Assuming all sources of systematic uncertainty are independent and adding them in quadrature, the total systematic uncertainty is 7.3 MeV/$c^2$ for the mass, and 17.5 MeV for the width of the $h_1(1380)$.

### Table I. Systematic uncertainties for the $h_1(1380)$ resonance parameters.

| Source          | $M$ (MeV/$c^2$) | $\Gamma$ (MeV) |
|-----------------|-----------------|---------------|
| Mass calibration| 1.1             | –             |
| Mass resolution | –               | 1.8           |
| Signal shape    | 2.1             | 4.7           |
| Background shape| 6.8             | 16.7          |
| Fit range       | 1.1             | 1.4           |
| Total           | 7.3             | 17.5          |

Systematic uncertainties in the branching fraction measurements come from the uncertainties in the number of $J/\psi$ events, tracking efficiency, particle identifi-
cation, photon detection, $K_S^0$ reconstruction, kinematic fit, mass window requirements, fitting procedure, peaking background estimation, and the branching fractions of intermediate state decays.

In Refs. 13, 14, the number of $J/\psi$ events is determined with an uncertainty of 0.6%. The uncertainty of the tracking efficiency is estimated to be 1.0% per photon, as obtained from a study of the high-purity control sample of $J/\psi \rightarrow \rho \pi$ [25]. For $K_S^0$ reconstruction, the uncertainty is studied with a control sample of $J/\psi \rightarrow K^+(892)\mp K^\mp \rightarrow K_S^0 K^\mp \pi^\mp$. A conservative value of 3.5% is taken as the systematic uncertainty. The uncertainty associated with the kinematic fit comes from the inconsistency between data and MC simulation of the track helix parameters and the error matrices. Following the procedure described in Ref. 26, we take the difference between the efficiencies with and without the helix parameter correction as the systematic uncertainty, which is 2.8% in the $\eta'/K^-\pi^0$ mode and 1.6% in the $\eta/K^0 S K^+\pi^-$ mode. The uncertainties arising from the $\pi^0$, $\eta$, $\eta'$ and $K_S^0$ selection are estimated by varying the mass window requirements. To estimate the uncertainties from the choice of signal shape, background shape and fit range: for $K^+(892)$ signal fit, the signal shape is changed from the MC shape to a Breit-Wigner function convolved with a Gaussian function; the background shape is varied from a polynomial function to the MC shape plus the non-$\eta'$ sideband, and the fit range is also varied; for the $h_1(1380)$ signal fit, the methods are following the $h_1(1380)$ resonance parameters study described above. The peaking background from the $K^+(892)$ is estimated using the non-$\eta'$ and non-$\pi^0$ sidebands. The uncertainties associated with the branching fractions of intermediate states are taken from the PDG [1]. The total systematic uncertainties in the branching fractions are determined to be 14.1% and 12.6% for $B(J/\psi \rightarrow \eta h_1(1380)) \times B(h_1(1380) \rightarrow K^+(892)+K^-+c.c.)$ and $B(J/\psi \rightarrow \eta' h_1(1380)) \times B(h_1(1380) \rightarrow K^+(892)+K^-+c.c.)$, respectively, for the $\eta K^+ K^- \pi^0$ final states, and 13.3%, 11.8% and 12.9% for $B(J/\psi \rightarrow \eta h_1(1380)) \times B(h_1(1380) \rightarrow K^+(892)+c.c.)$, $B(J/\psi \rightarrow \eta' h_1(1380)) \times B(h_1(1380) \rightarrow K^+(892)+K^-+c.c.)$ and $B(J/\psi \rightarrow \eta K^+(892)K^0+K^-+c.c.)$, respectively, for $\eta K_S^0 K^+\pi^-$ final states, as summarized in Table III.

The mixing angle $\theta_{p_1}$ between the $h_1(1170)$ and $h_1(1380)$ is calculated with the relation
\[
\tan \theta_{p_1} = \frac{m_{p_1}^2 - m_{h_1}^2}{\sqrt{m_{h_1}^2 (m_{h_1}^2 - m_{h_1}^2) - m_{p_1}^2 m_{h_1}^4}}.
\]

where $m_{h_1}$ and $m_{p_1}$ are the masses of $h_1(1380)$ and $h_1(1170)$, respectively, and $m_{p_1}^2$ is the mass squared of the octet state $^1p_1$, applying the Gel-Mann-Okubo relations [27], obtained as
\[
m_{S}^2(p_1) \equiv m_2^2 \equiv \frac{1}{3}(4m_{K_{1B}}^2 - m_{b_1}^2).
\]

Finally, $m_{K_{1B}}$ is the mass of the flavor eigenstate $K_{1B}$ as obtained from the relation
\[
m_{K_{1B}}^2 = m_{K_{1B}(1400)}^2 \sin^2 \theta_K + m_{K_{1B}(1270)}^2 \cos^2 \theta_K.
\]

FIG. 6. Fits to the $M(K^+(892)K^-)$ distributions with interference between signal and background. Dots with error bars are data; the solid curves show the total fits; the dot-dashed curves are the background; the dotted curves are the $h_1(1380)$ signal; and the short-dashed curves are the interference between signal and background.
TABLE II. Systematic uncertainties in the branching fractions of $B(J/\psi \rightarrow \eta' h_4(1380)) \times B(h_1(1380) \rightarrow K^*(892)\bar{K} + c.c.)$ and $B(J/\psi \rightarrow \eta' K^*(892)\bar{K} + c.c.)$ (in %).

| Source | $\eta' h_1(1380)$ | $\eta' h_1(1380)$ | $\eta' K^{*\pm} K^+ + c.c.$ | $\eta' K^{*\pm} K^+ + c.c.$ | $\eta' K^{*\pm} K^0 + c.c.$ | $\eta' K^{*\pm} K^{0\mp} + c.c.$ |
|--------|------------------|------------------|----------------|----------------|----------------|----------------|
| Number of $J/\psi$ | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 |
| MDC tracking | 4.0 | 6.0 | 6.0 | 6.0 | 6.0 | 6.0 |
| Photon detection | 4.0 | 2.0 | 4.0 | 2.0 | 2.0 | 2.0 |
| Particle identification | 8.0 | 8.0 | 8.0 | 8.0 | 8.0 | 8.0 |
| $K^0_S$ reconstruction | 2.2 | 3.5 | 3.5 | 3.5 | 3.5 | 3.5 |
| $4\pi$ kinematic fit | 2.8 | 1.6 | 2.8 | 1.6 | 1.6 | 1.6 |
| $\pi^0$ selection | 0.3 | 0.2 | 0.2 | 0.1 | 0.1 | 0.1 |
| $\eta$ selection | 3.4 | 3.6 | 3.6 | 0.6 | 0.6 | 0.6 |
| $\eta'$ selection | 2.2 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 |
| $K^*(892)$ selection | 2.2 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 |
| Signal shape | 5.3 | 5.5 | 5.5 | 3.2 | 3.2 | 3.2 |
| Background shape | 6.0 | 2.6 | 3.8 | 1.6 | 1.6 | 1.6 |
| Fit range | 3.0 | 2.2 | 0.8 | 0.4 | 0.4 | 0.4 |
| $K^*(892)$ Peaking background | 3.4 | 3.6 | 0.8 | 0.6 | 0.6 | 0.6 |
| Branching fraction | 1.7 | 1.7 | 1.7 | 1.7 | 1.7 | 1.7 |
| Total | 14.1 | 13.3 | 12.6 | 11.8 | 11.8 | 12.9 |

This result is consistent with the ideal decoupling angle $35.26^\circ$ and theoretical expectations of $(32.3\pm1.0)^{\circ}$ or $(38.3\pm1.0)^{\circ}$ by the Hadron Spectrum Collaboration [28].

In summary, based on a sample of $1.31\times10^9$ $J/\psi$ events collected by the BESIII experiment, we report the first observation of $J/\psi \rightarrow \eta' h_4(1380)$, where $h_4(1380) \rightarrow K^*(892)\bar{K} + c.c.$ and the mass and width of the $h_1(1380)$ are determined to be $M = (1423.2 \pm 2.1 \pm 7.3)$ MeV/c$^2$ and $\Gamma = (90.3 \pm 9.8 \pm 17.5)$ MeV, where the uncertainty from the interference is not included. This measurement is consistent with the previous measurements by the LASS, Crystal Barrel and BESIII collaborations [2,3,12] with improved precision. The product branching fractions of $h_1(1380)$ production and three body decays are also measured and isospin symmetry violation is found in $h_1(1380)$ decays between $h_1(1380) \rightarrow K^*(892)^+K^- + c.c.$ and $h_1(1380) \rightarrow K^*(892)^0\bar{K}^0 + c.c.$ Additionally, based on the measured $h_1(1380)$ mass, the mixing angle between the $h_1(1170)$ and $h_1(1380)$ is determined to be $(35.9 \pm 2.6)^{\circ}$ assuming the preferred mixing angle between the $K^A_1$ and $K^B_1$ of $34^{\circ}$. The measured mixing angle supports the hypothesis that the quark contents of the $h_1(1380)$ is predominantly $u\bar{u} + d\bar{d}$. The BESIII collaboration thanks the staff of BEPCII, the IHEP computing center and the supercomputing center of USTC for their strong support. This work is supported in part by National Key Basic Research Program of China under Contract No. 2015CB856700; National Natural Science Foundation of China (NSFC) under Contracts Nos. 11125525, 11235011, 11322544, 11335008, 11425524, 11625523, 11635010, 11375170, 11275189, 11475164, 11475169, 11605196, 11605198, 11705192, 11735014; the Chinese Academy of Sciences (CAS) Large-Scale Scientific Facility Program; the CAS Center for Excellence in Particle Physics (CCEPP); the Collaborative Innovation Center for Particles and Interactions (CICPI); Joint Large-Scale Scientific Facility Funds of the NSFC and CAS under Contracts Nos. U1232201, U1332201, U1532257, U1532258, U1533202, U1732263; CAS under Contracts Nos. KJCX2-YW-N29, KJCX2-YW-N47, KYCDD-JSSW-SLH003; 100 Talents Program of CAS; National 1000 Talents Program of China; INPAC and Shanghai Key Laboratory for Particle Physics and Cosmology; German Research Foundation DFG under Contracts Nos. Collaborative Research Center CRC 1044, FOR 2359; Istituto Nazionale di Fisica Nucleare, Italy; Joint Large-Scale Scientific Facility Funds of the NSFC and CAS; Koninklijke Nederlandse Akademie van Wetenschappen (KNAW) under Contract No. 230-4CFD03; Ministry of Development of Turkey under Contract No. DPT2006K-120470; National Natural Science Foundation of China (NSFC); National Science and Technology fund; The Swedish Research Council; U. S. Department of Energy under Contracts Nos. DE-FG02-05ER41374, DE-SC-0001194, DE-SC-00010504, DE-SC-00012069; U.S. National Science Foundation; University of Groningen (RuG) and the Helmholtzentrum fuer Schwerionenforschung GmbH (GSI), Darmstadt; WCU Program of National Research Foundation of Korea under Contract No. R32-2008-000-10155-0.

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| Source | $b_1(1235)$ | $K_1(1400)$ | $K_1(1270)$ | $h_1(1170)$ | $h_1(1380)$ | Total |
|--------|-------------|-------------|-------------|-------------|-------------|-------|
| Value  | 0.7         | 2.1         | 4.2         | 4.1         | 3.6         | 7.2   |

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