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$\psi(2S)$ two- and three-body hadronic decays

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We report measurements of branching fractions for $\psi(2S)$ decays into $\omega\pi^+\pi^-$, $b_1\pi$, $\omega f_2(1270)$, ωK^+K^-, $\omega p\bar{p}$, $\phi\pi^+\pi^-$, $\phi f_0(980)$, ϕK^+K^-, and an upper limit for $\phi p\bar{p}$ final states based on a data sample of $(4.02 \pm 0.22) \times 10^6$ $\psi(2S)$ events collected with the BESI detector at the Beijing Electron-Positron Collider. The branching fractions for $b_1\pi$ and $\omega f_2(1270)$ update previous BES results, while those for other decay modes are first measurements. The ratios of $\psi(2S)$ and J/ψ branching fractions are smaller than what is expected from the 12% rule by a factor of six for $\omega f_2(1270)$, by a factor of two for $\omega\pi^+\pi^-$, $\omega p\bar{p}$, and ϕK^+K^-, while for other studied channels the ratios are consistent with expectation within errors.

I. INTRODUCTION

In perturbative QCD, the charmonium states, J/ψ and $\psi(2S)$, are considered to be non-relativistic bound states of charm and anticharm quarks, and their decays into light hadrons are expected to be dominated by the annihilation of the constituent c and $\bar{c}$ quarks into three gluons. In this simple picture, the partial width for decays into any exclusive hadronic state h is proportional to the wave function at the origin squared, $|\psi(0)|^2$, which is well determined from dilepton decays. Since the strong coupling constant α_s does not change much between the J/ψ and $\psi(2S)$ masses, it is reasonable to expect that, for any exclusive hadronic state h, the J/ψ and $\psi(2S)$ decay branching fractions will scale as [1]

$$\frac{B(\psi(2S) \to h)}{B(J/\psi \to h)} \simeq \frac{B(\psi(2S) \to e^+e^-)}{B(J/\psi \to e^+e^-)} \simeq 12\%,$$

where the leptonic branching fractions are taken from the PDG tables [2]. This relation is known as the "12% rule". Although the rule works reasonably well for a number of specific decay modes, it fails severely in the case of the $\psi(2S)$ two-body decays to the vector-pseudoscalar (VP) meson final states, $\rho\pi$ and $K^*\bar{K}$ [3,4]. This anomaly is commonly called the $\rho\pi$ *puzzle*. In addition, the BES group has reported violations of the 12% rule for vector-tensor (VT) decay modes [5]. Although a number of theoretical explanations have been proposed to explain this puzzle [1,6], it seems that most of them do not provide a satisfactory solution.

In this paper, the measurements of the branching fractions of $\psi(2S)$ decays into $\omega\pi^+\pi^-$, $b_1\pi$, $\omega f_2(1270)$, ωK^+K^-, $\omega p\bar{p}$, $\phi\pi^+\pi^-$, $\phi f_0(980)$, ϕK^+K^-, and $\phi p\bar{p}$ final states are presented. The results are compared with the corresponding J/ψ branching fractions to test the 12% rule for these two-body and three-body hadronic decays.

II. THE BES DETECTOR

The BEijing Spectrometer, BES, is a conventional cylindrical magnetic spectrometer that is coaxial with the colliding e^+e^- beams of the Beijing Electron-Positron Collider, BEPC. BESI is described in detail in ref. [7]. A four-layer central drift chamber (CDC) surrounding the beam pipe provides trigger information. Outside the CDC, the forty-layer main drift chamber (MDC) provides tracking and energy-loss (dE/dx) information on charged tracks over 85% of the total solid angle. The momentum resolution for charged tracks is $\sigma_p/p = 0.017\sqrt{1+p^2}$ (p in GeV/c), and the dE/dx resolution for hadron tracks in these measurements is about 9%. An array of 48 scintillation counters surrounding the MDC provides measurements of the time-of-flight (TOF) of charged tracks with a resolution of about 450 ps for hadrons. Outside the TOF system is a 12 radiation length thick lead-gas barrel shower counter (BSC) that operates in self-quenching streamer mode and detects electrons and photons over 80% of the total solid angle. The BSC energy resolution is $\sigma_E/E = 0.22/\sqrt{E}$ (E in GeV), and its spatial resolution for photons is $\sigma_\phi = 4.5$ mrad and $\sigma_\theta = 12$ mrad. A solenoidal magnet surrounds the BSC and provides a 0.4 Tesla magnetic field in the central tracking region of the detector. Outside the solenoidal coil, there are three double layers of proportional chambers interspersed with the magnet flux return iron to identify muons of momentum greater than 0.5 GeV/c.

III. EVENT SELECTION

A. Data sample and event topologies

The data sample used for this analysis consists of $(4.02 \pm 0.22) \times 10^6$ $\psi(2S)$ events collected with BES/BEPC at the center-of-mass energy $\sqrt{s} = M_{\psi(2S)}$. The decay channels investigated are $\psi(2S)$ into $\omega\pi^+\pi^-$, $b_1\pi$, $\omega f_2(1270)$, ωK^+K^-, $\omega p\bar{p}$, $\phi\pi^+\pi^-$,

$\phi f_0(980)$, ϕK^+K^-, and $\phi p\bar{p}$ final states, where b_1 decays to $\omega\pi$, ω to $\pi^+\pi^-\pi^0$, ϕ to K^+K^-, and $f_2(1270)$ and $f_0(980)$ to $\pi^+\pi^-$. They are all four-prong events or four-prong plus two photon events.

B. Photon and charged particle identification

A neutral cluster is considered to be a photon candidate if the following requirements are satisfied: it is located within the BSC fiducial region ($|\cos\theta| < 0.8$), the energy deposited in the BSC is greater than 50 MeV, the first hit appears in the first 6 radiation lengths, the angle in the xy plane (perpendicular to beam direction) between the cluster and the nearest charged track is greater than 16°, and the angle between the cluster development direction in the BSC and the photon emission direction from the beam interaction point (IP) is less than 37°. With these criteria applied to the $\psi(2S) \to \pi^+\pi^- p\bar{p}$ sample selected by four-constraint (4C) kinematic fitting, less than 20% of events have photon candidates, which indicates an adequate fake-photon rejection (see Fig. 1).

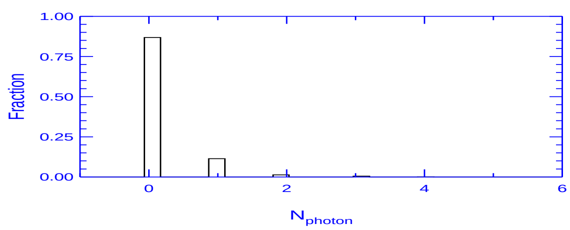

FIG. 1. The distribution of the number of photon candidates found in kinematically selected $\psi(2S) \to \pi^+\pi^- p\bar{p}$ events.

Each charged track is required to be well fit by a three-dimensional helix, to originate from the IP region, $V_{xy} = \sqrt{V_x^2 + V_y^2} < 2$ cm and $|V_z| < 20$ cm, and to have a polar angle $|\cos\theta| < 0.8$. Here V_x, V_y, and V_z are the x, y, and z coordinates of the point of closest approach to the beam axis. The time of flight (TOF) and dE/dx measurements for each charged track are used to calculate χ^2 values for the hypotheses that a track is a pion, kaon, or proton, for the purpose of particle identification.

C. Monte Carlo simulations

Phase space Monte Carlo (MC) event generators and the BES detector simulation package, SOBER [7], are used for simulating events for all channels analyzed. To determine detection efficiencies, MC generated events are subjected to the same reconstruction and event selection criteria as those applied to the real data. For each channel, 30,000 MC events are generated.

D. Event selection criteria

For all analyzed decay channels, the candidate events are required to satisfy the following general selection criteria:

1. The number of charged particles must be equal to four with net charge zero.

2. The number of photon candidates must be equal to or greater than two for the decay channels containing π^0.

3. For each charged track in an event, the $\chi^2_{PID}(i)$ and its corresponding $Prob_{PID}(i)$ values are calculated based on the measurements of dE/dx in the MDC and the time of flight in the TOF, with definitions

$$\chi^2_{PID}(i) = \chi^2_{dE/dx}(i) + \chi^2_{TOF}(i)$$

$$Prob_{PID}(i) = Prob(\chi^2_{PID}(i), ndf_{PID}),$$

where $ndf_{PID} = 2$ is the number of degrees of freedom in the $\chi^2_{PID}(i)$ determination and $Prob_{PID}(i)$ signifies the probability of this track having a particle i assignment. For final states containing $p\bar{p}$, we require at least one of the charged tracks satisfy $Prob_{PID}(p/\overline{p}) > 0.01 > Prob_{PID}(\pi/K)$, while for other channels analyzed, the probability of a charged track for a candidate particle assignment is required to be greater than 0.01.

4. A 4C (4 prong events) or 5C (4 prong plus two photon events) kinematic fit is performed for each event. To be selected for any candidate final state, the event probability given by the fit must be greater than 0.01.

5. The combined χ^2, χ^2_{com}, is defined as the sum of the χ^2 values of the kinematic fit and those from each of the four particle identification assignments:

$$\chi^2_{com} = \sum_i \chi^2_{PID}(i) + \chi^2_{kine},$$

which corresponds to the combined probability:

$$Prob_{com} = Prob(\chi^2_{com}, ndf_{com}),$$

where ndf_{com} is the corresponding total number of degrees of the freedom in the χ^2_{com} determination. The final state with the largest $Prob_{com}$ is taken as the candidate assignment for each event.

6. A cut on R_{Ep} is imposed to reject possible contamination from $\psi(2S) \to \pi^+\pi^- J/\psi$ and $\eta J/\psi$, with $J/\psi \to e^+e^-$, where

$$R_{Ep} = (\frac{E^+_{sc}}{p_+} - 1)^2 + (\frac{E^-_{sc}}{p_-} - 1)^2,$$

and p_+ (p_-)is the momentum of positive (negative) charged track measured with the MDC, and E^+_{sc} (E^-_{sc}) is the energy deposited in the BSC by the positive (negative) charged track.

7. Hit information from the muon chambers is used to reject possible muon tracks to reduce contamination from $\psi(2S) \to \pi^+\pi^- J/\psi$ and $\eta J/\psi$, where $J/\psi \to \mu^+\mu^-$.

1. $\psi(2S) \to \omega p\bar{p}$

The combined probability for the assignment of $\psi(2S) \to \pi^+\pi^-\pi^0 p\bar{p}$ is required to be larger than those of $\psi(2S) \to \pi^+\pi^-\pi^0\pi^+\pi^-$ and $\psi(2S) \to \pi^+\pi^-\pi^0 K^+K^-$. We impose a cut of $|m^{\pi^+\pi^-}_{recoil} - m_{J/\psi}| > 0.05$ GeV to reject backgrounds from $\psi(2S) \to \pi^+\pi^- J/\psi$, where $m^{\pi^+\pi^-}_{recoil}$ is the mass recoiling against the assigned $\pi^+\pi^-$ pair. A requirement of $m_{p\bar{p}} < m_{\psi(2S)} - m_\omega = 2.9$ GeV is applied to reject the backgrounds from $\psi(2S) \to \eta J/\psi \to \pi^+\pi^-\pi^0 p\bar{p}$ and $\pi^+\pi^-\pi^0\mu^+\mu^-$. Possible background could come from the decay of $\psi(2S) \to \pi^0\pi^0 J/\psi$, $J/\psi \to p\bar{p}\pi^+\pi^-$, where one of the π^0s is missed in the BES detector. However, MC simulation shows that after our selection criteria, the $\pi^+\pi^-\pi^0$ system from this process has a negligible contribution in the ω mass region. Also, due to the tiny branching fraction, the contamination from the decay of $\psi(2S) \to \pi^0 J/\psi$, $J/\psi \to \pi^+\pi^- p\bar{p}$ is negligible.

The $\pi^+\pi^-\pi^0$ invariant mass distribution for the events that survive all selection requirements is shown in Fig. 2, where a clean ω signal can be seen. A Breit-Wigner resonance convoluted with Gaussian mass resolution function plus a polynomial background is fitted to the data using an unbinned maximum likelihood method. In the fit, the mass resolution is fixed to its MC-determined value, and the width of the ω is fixed to its PDG value. The fit gives 14.9 ± 5.8 signal events with statistical significance 2.6σ, and with the MC-determined efficiency of 5.4%, we determine the branching fraction

$$B(\psi(2S) \to \omega p\bar{p}) = (0.8 \pm 0.3 \pm 0.1) \times 10^{-4},$$

where the first error is statistical and the second error systematic. Determination of the systematic errors is described in section IV.

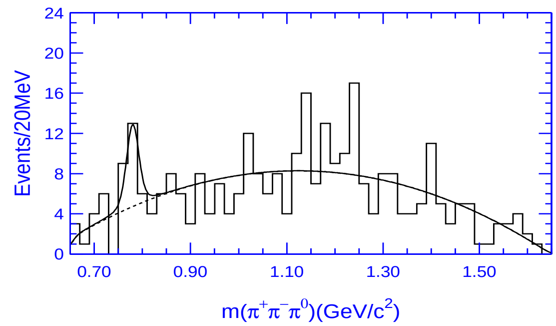

FIG. 2. The $\pi^+\pi^-\pi^0$ invariant mass distribution for candidate $\psi(2S) \to \omega p\bar{p}$ events.

2. $\psi(2S) \to \omega K^+K^-$

For this channel, the final state ($\pi^+\pi^-\pi^0 K^+K^-$) is similar to that of the previous channel ($\pi^+\pi^-\pi^0 p\bar{p}$) except $p\bar{p}$ is replaced by K^+K^-. Therefore, similar selection criteria are imposed, but the combined probability for the assignment of $\psi(2S) \to \pi^+\pi^-\pi^0 K^+K^-$ must be larger than those of $\psi(2S) \to \pi^+\pi^-\pi^0\pi^+\pi^-$ and $\psi(2S) \to \pi^0 K^+K^-K^+K^-$. A cut of $|m^{\pi^+\pi^-}_{recoil} - m_{J/\psi}| > 0.05$ GeV is used to reject backgrounds from $\psi(2S) \to \pi^+\pi^- J/\psi$. We require $m_{K^+K^-} < m_{\psi(2S)} - m_\omega = 2.9$ GeV to reject backgrounds from $\psi(2S) \to \eta J/\psi \to \pi^+\pi^-\pi^0 K^+K^-$. The contamination from the decay of $\psi(2S) \to \pi^0 J/\psi, J/\psi \to \pi^+\pi^- K^+K^-$ is negligible due to its tiny branching fraction. Although our selection criteria can not completely eliminate the contamination from $\psi(2S) \to K^0_s K^\pm \pi^\mp \pi^0$, $K^0_s \to \pi^+\pi^-$ decay, the invariant mass distribution of $m_{\pi^+\pi^-\pi^0}$ from this background is smooth, and therefore it will not affect the determination of the signal events.

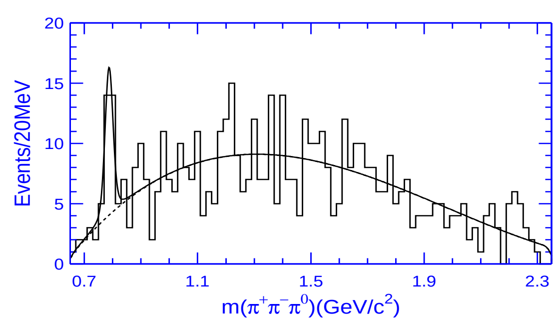

FIG. 3. The $\pi^+\pi^-\pi^0$ invariant mass distribution for candidate $\psi(2S) \to \omega K^+K^-$ events.

Figure 3 shows the $\pi^+\pi^-\pi^0$ invariant mass distribution for ωK^+K^- candidates. The polynomial backgrounds include the contamination from $\psi(2S) \to K_s^0 K^\pm \pi^\mp \pi^0$, $K_s^0 \to \pi^+\pi^-$. A fit gives 23.0 ± 5.2 signal events with a statistical significance of 6.3 σ. The detection efficiency for this decay mode is 4.4%, and we determine the branching fraction

$$B(\psi(2S) \to \omega K^+K^-) = (1.5 \pm 0.3 \pm 0.2) \times 10^{-4}.$$

3. $\psi(2S) \to \omega\pi^+\pi^-$

The candidate events for this decay mode have the final state $\pi^+\pi^-\pi^0\pi^+\pi^-$. To be selected, the combined probability for the assignment of $\psi(2S) \to \pi^+\pi^-\pi^0\pi^+\pi^-$ must be larger than that of $\psi(2S) \to \pi^+\pi^-\pi^0K^+K^-$. A cut of $|m_{recoil}^{\pi^+\pi^-} - m_{J/\psi}| > 0.05$ GeV rejects the backgrounds from $\psi(2S) \to \pi^+\pi^- J/\psi$, $J/\psi \to \pi^+\pi^-\pi^0$. We require $m_{\pi^+\pi^-} < m_{\psi(2S)} - m_\omega = 2.9$ GeV to reject the backgrounds from $\psi(2S) \to \eta J/\psi \to \pi^+\pi^-\pi^0\pi^+\pi^-$ and $\pi^+\pi^-\pi^0\mu^+\mu^-$, where $m_{\pi^+\pi^-}$ is the invariant mass of the $\pi^+\pi^-$ against the ω determined by the kinematic fit. The contamination from the decay of $\psi(2S) \to \pi^0 J/\psi$, $J/\psi \to \pi^+\pi^-\pi^+\pi^-$ is negligible due to its tiny branching fraction.

Figure 4 shows the the $\pi^+\pi^-\pi^0$ invariant mass distribution for $\omega\pi^+\pi^-$ candidates, where the polynomial backgrounds contain the contamination from $\psi(2S) \to K_s^0 K^\pm \pi^\mp \pi^0$, $K_s^0 \to \pi^+\pi^-$. A fit gives 100 ± 12 signal events. The detection efficiency for this decay mode is 5.8%, and we determine the branching fraction

$$B(\psi(2S) \to \omega\pi^+\pi^-) = (4.8 \pm 0.6 \pm 0.7) \times 10^{-4}.$$

4. $\psi(2S) \to b_1\pi$

The dominant decay mode of the b_1 is $b_1 \to \omega\pi$, and we assume its branching fraction is 100%. Therefore, the final state for this mode is the same as for $\psi(2S) \to \omega\pi^+\pi^-$. We use the same criteria as those for $\psi(2S) \to \omega\pi^+\pi^-$ to select candidate events, but an additional cut $|m_{\pi^+\pi^-\pi^0} - m_\omega| < 0.03$ GeV is applied to select events containing the ω particle. The Dalitz plot is shown in Fig. 5. The dense clusters in the top-left and in the bottom-right of the scatter plots (d) and (e) indicate a clear b_1 signal. Figure 6 shows the $\omega\pi$ invariant mass distribution for $b_1\pi$ candidates. In the fit, the mass and width of the b_1 are fixed to the PDG values. A fit gives 61 ± 11 signal events. The detection efficiency for this decay mode is 5.2%, and we determine the branching fraction

$$B(\psi(2S) \to b_1\pi) = (3.2 \pm 0.6 \pm 0.5) \times 10^{-4}.$$

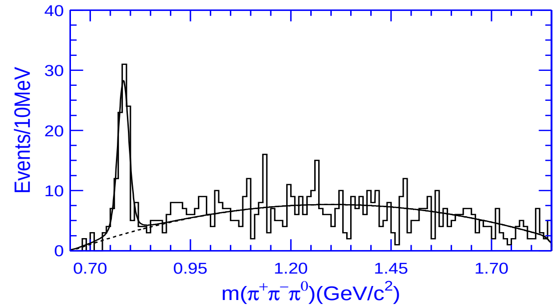

FIG. 4. The $\pi^+\pi^-\pi^0$ invariant mass distribution for candidate $\psi(2S) \to \omega\pi^+\pi^-$ events.

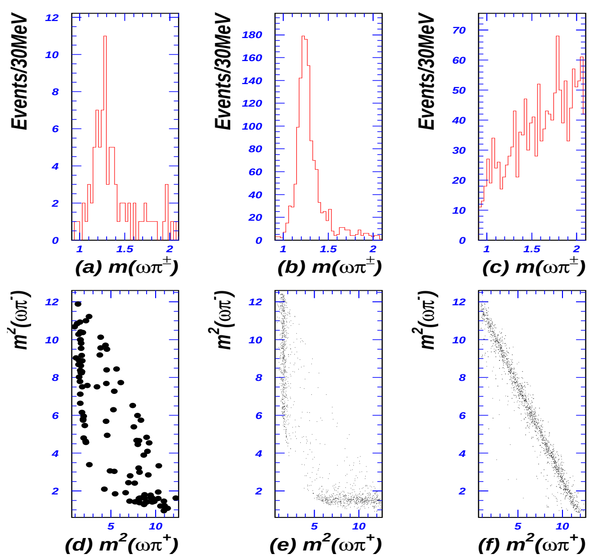

FIG. 5. The Dalitz plot (a,d) for $\psi(2S) \to \omega\pi^+\pi^-$ (data); (b,e) for $\psi(2S) \to b_1\pi$ (MC); and (c,f) for $\psi(2S) \to \omega f_2(1270)$ (MC) events, respectively.

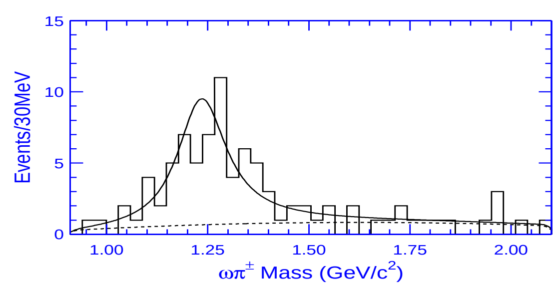

FIG. 6. The $\omega\pi$ invariant mass distribution for candidate $\psi(2S) \to b_1\pi$ events.

5. $\psi(2S) \to \omega f_2(1270)$

The final state for this decay mode is also the same as for $\psi(2S) \to \omega\pi^+\pi^-$. We use the same criteria as those for $\psi(2S) \to \omega\pi^+\pi^-$, but impose an additional cut $|m_{\pi^+\pi^-\pi^0} - m_\omega| < 0.03$ GeV to select events containing an ω particle. A requirement of $|m_{\omega\pi} - m_{b_1}| > 0.2$ GeV is applied to remove contamination from the $b_1\pi$ channel. Figure 7 shows the $\pi^+\pi^-$ invariant mass distribution for $\psi(2S) \to \omega f_2(1270)$ candidates; it shows a visible bump in the $f_2(1270)$ mass region, in addition to the broad distribution in the lower mass region, which is presumably attributed to $f_0(400-1200)$ [8] production. A fit gives 10.2 ± 4.9 signal events with the mass and width of the $f_2(1270)$ fixed to its PDG values, the statistical significance is about 2.1σ. The detection efficiency for this decay mode is 4.8%, and we determine the branching fraction

$$B(\psi(2S) \to \omega f_2(1270)) = (1.1 \pm 0.5 \pm 0.2) \times 10^{-4},$$

or an upper limit of 1.5×10^{-4} (90% C.L.).

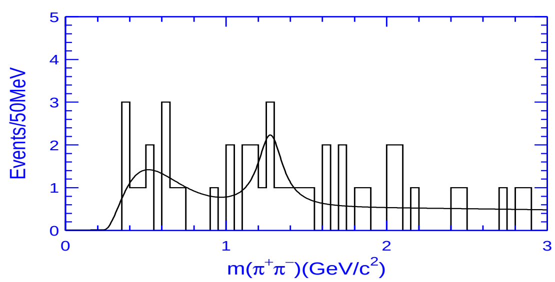

FIG. 7. The $\pi^+\pi^-$ invariant mass distribution for candidate $\psi(2S) \to \omega f_2(1270)$ events.

6. $\psi(2S) \to \phi\pi^+\pi^-$

The candidate events for this decay mode have a final state $K^+K^-\pi^+\pi^-$. The combined probability for the assignment of $\psi(2S) \to K^+K^-\pi^+\pi^-$ is required to be larger than those of $p\bar{p}\pi^+\pi^-$, $\pi^+\pi^-\pi^+\pi^-$, $K^+K^-K^+K^-$, and $K^\pm\pi^\mp\pi^+\pi^-$. A cut of $|m^{\pi^+\pi^-}_{recoil} - m_{J/\psi}| > 0.05$ GeV rejects possible backgrounds from $\psi(2S) \to \pi^+\pi^-J/\psi$. The decay of $\psi(2S) \to K^*K^-\pi^+(+c.c.) \to K^+K^-\pi^+\pi^-$ has a smooth $m_{K^+K^-}$ distribution below 1.06 GeV and therefore does not affect the $\phi\pi^+\pi^-$ signal. No K^0_s signal is found in the $m_{\pi^+\pi^-}$ invariant mass distribution for the selected data sample, indicating negligible $K^0_sK^\pm\pi^\mp$ background. Figure 8 shows the K^+K^- invariant mass distribution for $\psi(2S) \to \phi\pi^+\pi^-$ candidates, where a prominent ϕ signal can be seen. A fit gives 51.5 ± 8.3 signal events with the width of the ϕ fixed to its PDG value. The detection efficiency for this decay mode is 17.8%, and we determine the branching fraction

$$B(\psi(2S) \to \phi\pi^+\pi^-) = (1.5 \pm 0.2 \pm 0.2) \times 10^{-4}.$$

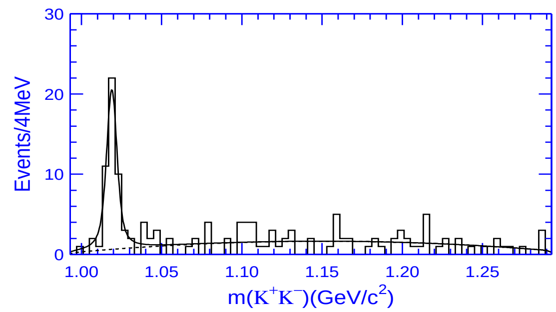

FIG. 8. The K^+K^- invariant mass distribution for candidate $\psi(2S) \to \phi\pi^+\pi^-$ events.

7. $\psi(2S) \to \phi f_0(980)$

We use the same criteria as those for $\phi\pi^+\pi^-$ for this decay mode, but with an additional requirement $|m_{K^+K^-} - m_\phi| < 0.02$ GeV to select events containing a ϕ particle. The $\pi^+\pi^-$ invariant mass distribution in Fig. 9 shows a clear $f_0(980)$ peak. A fit gives 18.4 ± 6.4 signal events with a width of about 45 MeV. The detection efficiency for this decay mode is 17.0%, and we determine the branching fraction

$$B(\psi(2S) \to \phi f_0(980)) \cdot B(\phi f_0(980) \to \pi^+\pi^-)$$

$$= (0.6 \pm 0.2 \pm 0.1) \times 10^{-4}.$$

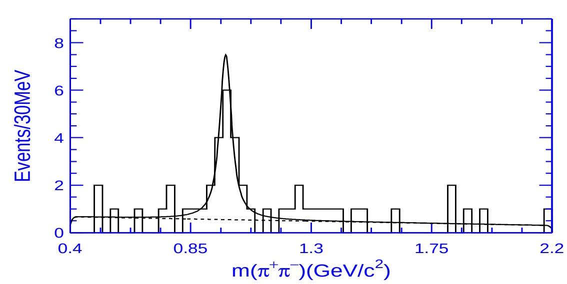

FIG. 9. The $\pi^+\pi^-$ invariant mass distribution for candidate $\psi(2S) \to \phi f_0(980)$ events.

8. $\psi(2S) \to \phi K^+K^-$

Here the combined probability for the assignment of $\psi(2S) \to K^+K^-K^+K^-$ is required to be larger than those of $p\bar{p}K^+K^-$, $K^+K^-\pi^+\pi^-$, and $\pi^+\pi^-\pi^+\pi^-$. The K^+K^- invariant mass distribution in Fig. 10 shows a clear ϕ peak. A fit gives 16.1 ± 5.0 signal events with the width of the ϕ fixed to its PDG value. The detection efficiency for this decay mode is 13.4%, and we determine the branching fraction

$$B(\psi(2S) \to \phi K^+K^-) = (0.6 \pm 0.2 \pm 0.1) \times 10^{-4}.$$

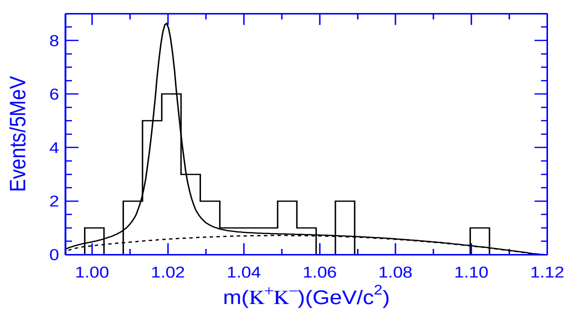

FIG. 10. The K^+K^- invariant mass distribution for candidate $\psi(2S) \to \phi K^+K^-$ events.

9. $\psi(2S) \to \phi p\bar{p}$

The combined probability for the assignment of $\psi(2S) \to K^+K^-p\bar{p}$ is required to be larger than those of $p\bar{p}\pi^+\pi^-$, $K^+K^-K^+K^-$, and $\pi^+\pi^-\pi^+\pi^-$. The K^+K^- invariant mass plot is shown in Fig. 11. Only four events appear in the ϕ mass region. Assuming zero background events and using a detection efficiency of 16.8%, we obtain the upper limit on the branching fraction of

$$B(\psi(2S) \to \phi p\bar{p}) < 0.26 \times 10^{-4} \quad (90\% \ \ C.L.)$$

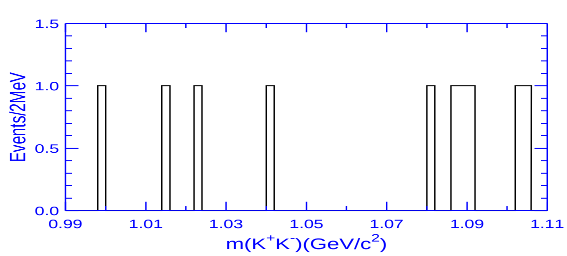

FIG. 11. The K^+K^- invariant mass distribution for candidate $\psi(2S) \to \phi p\bar{p}$ events.

IV. BRANCHING FRACTION DETERMINATION

For a process $\psi(2S) \to X$, the branching fraction is determined by the relation

$$B(\psi(2S) \to X) = \frac{n^{obs}(\psi(2S) \to X \to Y)}{N_{\psi(2S)} \cdot B(X \to Y) \cdot \epsilon(\psi(2S) \to X \to Y)},$$

where Y stands for the final state, X the intermediate state, and ϵ the detection efficiency. The branching fraction of $X \to Y$ is taken from the PDG [2]. The total number of $\psi(2S)$ events $N_{\psi(2S)} = (4.02 \pm 0.22) \times 10^6$ [9] is determined from the number of $\psi(2S) \to \pi^+\pi^-J/\psi$ events corrected for detection efficiency in the BES $\psi(2S)$ data sample $(1.227 \pm 0.003 \pm 0.017 \times 10^6)$ [10] and the PDG branching fraction [2].

A. Efficiency Corrections and Systematic errors

Because the Monte Carlo does not simulate real events exactly, it is necessary to correct the detection efficiency for the difference that the PID selection has on data and MC events and for the difference that kinematic selection has on data and MC events because of differences in the track fit error matrix elements. To correct for the PID difference, the efficiency is multiplied by a factor ranging from 0.89 to 0.98 with an uncertainty of 0.04 to 0.07, depending on channel; while the correction factor in kinematic fitting is 0.85 ± 0.05 and 0.88 ± 0.08 for 4-prong and 4-prong plus 2-photon final states, respectively [11].

Beside the uncertainties caused by the particle identification and the kinematic fitting stated above, a systematic error common to all decay modes is the uncertainty in the total number of $\psi(2S)$ events (5.4%). The uncertainties of the PDG values of the intermediate state ω, ϕ, b_1, $f_2(1270)$, and $f_0(980)$ decay branching fractions are also sources of systematic error (0.8% to 3.1%). The systematic error due to the statistical precision of the MC event samples ranges from 1.2% to 3.2%, depending on the decay channel. Difficulties in the simulation of low energy photons in the Monte Carlo give rise to a systematic error in the efficiency that varies from 4.5% to 8.6% depending on photon energy for the final states containing π^0. The systematic error from $\pi^0 \to 2\gamma$, where at least one photon is converted to a e^+e^- pair is about 1.4%. The variation of branching fraction results for different choices of the fiducial region is about 5%. The total systematic error is taken as the sum of the individual terms added in quadrature and ranges from 12% to 17%, depending on the channel.

B. Branching fraction results

The results, including numbers of signal events, detection efficiencies and branching fractions or upper limits (90% C.L.), are summarized in Table I. The first error of the branching fraction is statistical and the second is systematic for each channel. Among these, the branching fractions for $\omega f_2(1270)$ and $b_1^{\pm}\pi^{\mp}$ supersede previous BES results [5,12]; while all other branching fractions are first measurements for these decays. For $b_1^{\pm}\pi^{\mp}$, the difference is due to an improved understanding of the acceptance; for $\omega f_2(1270)$, the difference is due to improved selection criteria to reduce background.

To test the 12% rule, we also list in Table I the ratio Q_h of the $\psi(2S)$ and J/ψ branching fractions for each channel, where the J/ψ branching fractions are taken from the PDG. Among these channels, the ratio of $\omega f_2(1270)$ (VT mode) is suppressed by a factor of six with respect to the PQCD expectation, and those of $\omega\pi^+\pi^-$, $\omega p\bar{p}$, and ϕK^+K^- are suppressed by about a factor of two, those of other channels are consistent with PQCD expectation within errors.

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TABLE I. Branching fractions of $\psi(2S)$ and Q_h values for $\psi(2S)$ and J/ψ hadronic decays.*

Channel X	Number of Events	Efficiency (%)	$\frac{B_{\psi(2S)\to X}}{B_{\psi(2S)\to\pi^+\pi^- J/\psi}}$ (10^{-4})	$B_{\psi(2S)\to X}$ (10^{-4})	$B_{J/\psi\to X}$ (10^{-4})	$Q_X(\%)$ (%)
$\omega\pi^+\pi^-$	100 ± 12	5.8 ± 0.8	$15.8 \pm 1.9 \pm 2.2$	$4.8 \pm 0.6 \pm 0.7$	72.0 ± 12.0	6.7 ± 1.7
$b_1^\pm\pi^\mp$	61 ± 11	5.2 ± 0.7	$10.6 \pm 1.9 \pm 1.5$	$3.2 \pm 0.6 \pm 0.5$	30.0 ± 5.0	11 ± 3
$\omega f_2(1270)$	10.2 ± 4.9	4.8 ± 0.7	$3.4 \pm 1.7 \pm 0.5$	$1.1 \pm 0.5 \pm 0.2$	43.0 ± 6.0	2.4 ± 1.3
				< 1.5		
ωK^+K^-	23.0 ± 5.2	4.4 ± 0.6	$4.8 \pm 1.1 \pm 0.7$	$1.5 \pm 0.3 \pm 0.2$	7.4 ± 2.4	20 ± 8
$\omega p\bar{p}$	14.9 ± 5.8	5.4 ± 0.8	$2.5 \pm 1.0 \pm 0.4$	$0.8 \pm 0.3 \pm 0.1$	13.0 ± 2.5	6.0 ± 2.8
$\phi\pi^+\pi^-$	51.5 ± 8.3	17.8 ± 2.1	$4.8 \pm 0.8 \pm 0.6$	$1.5 \pm 0.2 \pm 0.2$	8.0 ± 1.2	18 ± 5
$\phi f_0(980)(f_0 \to \pi^+\pi^-)$	18.4 ± 6.4	17.0 ± 2.1	$1.8 \pm 0.6 \pm 0.2$	$0.6 \pm 0.2 \pm 0.1$		
$\phi f_0(980)$**			$3.4 \pm 1.2 \pm 0.4$	$1.1 \pm 0.4 \pm 0.1$	3.2 ± 0.9	33 ± 15
ϕK^+K^-	16.1 ± 5.0	13.4 ± 1.6	$2.0 \pm 0.6 \pm 0.2$	$0.6 \pm 0.2 \pm 0.1$	8.3 ± 1.3	7.3 ± 2.6
$\phi p\bar{p}$	4	16.8 ± 1.8	< 0.85	< 0.26	8.3 ± 1.3	< 58

* The upper limit is at the 90% confidence level; $B_{J/\psi}$ taken from PDG value.

** $B_{f_0\to\pi^+\pi^-} = 0.521 \pm 0.016$(PDG'96)