Measurements of $\psi(2S)$ decays into vector-tensor final states

J. Z. Bai,[1] Y. Ban,[10] J. G. Bian,[1] X. Cai,[1] J. F. Chang,[1] H. F. Chen,[16] H. S. Chen,[1] H. X. Chen,[1] J. Chen,[1] J. C. Chen,[1] Jun Chen,[6] M. L. Chen,[1] Y. B. Chen,[1] S. P. Chi,[2] Y. P. Chu,[1] X. Z. Cui,[1] H. L. Dai,[1] Y. S. Dai,[18] Z. Y. Deng,[1] L. Y. Dong,[1] S. X. Du,[1] Z. Z. Du,[1] J. Fang,[1] S. S. Fang,[2] C. D. Fu,[1] H. Y. Fu,[1] L. P. Fu,[6] C. S. Gao,[1] M. L. Gao,[1] Y. N. Gao,[14] M. Y. Gong,[1] W. X. Gong,[1] S. D. Gu,[1] Y. N. Guo,[1] Y. Q. Guo,[1] Z. J. Guo,[15] S. W. Han,[1] F. A. Harris,[15] J. He,[1] K. L. He,[1] M. He,[11] X. He,[1] Y. K. Heng,[1] H. M. Hu,[1] T. Hu,[1] G. S. Huang,[1] L. Huang,[6] X. P. Huang,[1] X. B. Ji,[1] Q. Y. Jia,[10] C. H. Jiang,[1] X. S. Jiang,[1] D. P. Jin,[1] S. Jin,[1] Y. Jin,[1] Y. F. Lai,[1] F. Li,[1] G. Li,[1] H. H. Li,[1] J. Li,[1] J. C. Li,[1] Q. J. Li,[1] R. B. Li,[1] R. Y. Li,[1] S. M. Li,[1] W. Li,[1] W. G. Li,[1] X. L. Li,[7] X. Q. Li,[7] X. S. Li,[14] Y. F. Liang,[13] H. B. Liao,[5] C. X. Liu,[1] Fang Liu,[16] F. Liu,[5] H. M. Liu,[1] J. B. Liu,[1] J. P. Liu,[17] R. G. Liu,[1] Y. Liu,[1] Z. A. Liu,[1] Z. X. Liu,[1] G. R. Lu,[4] F. Lu,[1] J. G. Lu,[1] C. L. Luo,[8] X. L. Luo,[1] F. C. Ma,[7] J. M. Ma,[1] L. L. Ma,[11] X. Y. Ma,[1] Z. P. Mao,[1] X. C. Meng,[1] X. H. Mo,[1] J. Nie,[1] Z. D. Nie,[1] S. L. Olsen,[15] H. P. Peng,[16] N. D. Qi,[1] C. D. Qian,[12] H. Qin,[8] J. F. Qiu,[1] Z. Y. Ren,[1] G. Rong,[1] L. Y. Shan,[1] L. Shang,[1] D. L. Shen,[1] X. Y. Shen,[1] H. Y. Sheng,[1] F. Shi,[1] X. Shi,[10] L. W. Song,[1] H. S. Sun,[1] S. S. Sun,[16] Y. Z. Sun,[1] Z. J. Sun,[1] X. Tang,[1] N. Tao,[16] Y. R. Tian,[14] G. L. Tong,[1] G. S. Varner,[15] D. Y. Wang,[1] J. Z. Wang,[1] L. Wang,[1] L. S. Wang,[1] M. Wang,[1] Meng Wang,[1] P. Wang,[1] P. L. Wang,[1] S. Z. Wang,[1] W. F. Wang,[1] Y. F. Wang,[1] Zhe Wang,[1] Z. Wang,[1] Zheng Wang,[1] Z. Y. Wang,[1] C. L. Wei,[1] N. Wu,[1] Y. M. Wu,[1] X. M. Xia,[1] X. X. Xie,[1] B. Xin,[7] G. F. Xu,[1] H. Xu,[1] Y. Xu,[1] S. T. Xue,[1] M. L. Yan,[16] W. B. Yan,[1] F. Yang,[9] H. X. Yang,[14] J. Yang,[16] S. D. Yang,[1] Y. X. Yang,[3] L. H. Yi,[6] Z. Y. Yi,[1] M. Ye,[1] M. H. Ye,[2] Y. X. Ye,[16] C. S. Yu,[1] G. W. Yu,[1] C. Z. Yuan,[1] J. M. Yuan,[1] Y. Yuan,[1] Q. Yue,[1] S. L. Zang,[1] Y. Zeng,[6] B. X. Zhang,[1] B. Y. Zhang,[1] C. C. Zhang,[1] D. H. Zhang,[1] H. Y. Zhang,[1] J. Zhang,[1] J. M. Zhang,[4] J. Y. Zhang,[1] J. W. Zhang,[1] L. S. Zhang,[1] Q. J. Zhang,[1] S. Q. Zhang,[1] X. M. Zhang,[1] X. Y. Zhang,[11] Yiyun Zhang,[13] Y. J. Zhang,[10] Y. Y. Zhang,[1] Z. P. Zhang,[16] Z. Q. Zhang,[4] D. X. Zhao,[1] J. B. Zhao,[1] J. W. Zhao,[1] P. P. Zhao,[1] W. R. Zhao,[1] X. J. Zhao,[1] Y. B. Zhao,[1] Z. G. Zhao,[1,*] H. Q. Zheng,[10] J. P. Zheng,[1] L. S. Zheng,[1] Z. P. Zheng,[1] X. C. Zhong,[1] B. Q. Zhou,[1] G. M. Zhou,[1] L. Zhou,[1] N. F. Zhou,[1] K. J. Zhu,[1] Q. M. Zhu,[1] Yingchun Zhu,[1] Y. C. Zhu,[1] Y. S. Zhu,[1] Z. A. Zhu,[1] B. A. Zhuang,[1] and B. S. Zou[1]

(BES Collaboration)

[1]*Institute of High Energy Physics, Beijing 100039, People's Republic of China*
[2]*China Center of Advanced Science and Technology, Beijing 100080, People's Republic of China*
[3]*Guangxi Normal University, Guilin 541004, People's Republic of China*
[4]*Henan Normal University, Xinxiang 453002, People's Republic of China*
[5]*Huazhong Normal University, Wuhan 430079, People's Republic of China*
[6]*Hunan University, Changsha 410082, People's Republic of China*
[7]*Liaoning University, Shenyang 110036, People's Republic of China*
[8]*Nanjing Normal University, Nanjing 210097, People's Republic of China*
[9]*Nankai University, Tianjin 300071, People's Republic of China*
[10]*Peking University, Beijing 100871, People's Republic of China*
[11]*Shandong University, Jinan 250100, People's Republic of China*
[12]*Shanghai Jiaotong University, Shanghai 200030, People's Republic of China*
[13]*Sichuan University, Chengdu 610064, People's Republic of China*
[14]*Tsinghua University, Beijing 100084, People's Republic of China*
[15]*University of Hawaii, Honolulu, Hawaii 96822, USA*
[16]*University of Science and Technology of China, Hefei 230026, People's Republic of China*
[17]*Wuhan University, Wuhan 430072, People's Republic of China*
[18]*Zhejiang University, Hangzhou 310028, People's Republic of China*

(Received 4 December 2003; published 2 April 2004)

Decays of the $\psi(2S)$ into vector plus tensor meson final states have been studied with 14 million $\psi(2S)$ events collected with the BESII detector. The branching fractions of $\psi(2S)\to\omega f_2(1270)$, $\rho a_2(1320)$, $K^*(892)^0\bar{K}_2^*(1430)^0+\text{c.c.}$, and $\phi f_2'(1525)$ are determined. They improve upon previous BESI results and confirm the violation of the "12%" rule for $\psi(2S)$ decays to VT channels with higher precision.

DOI: 10.1103/PhysRevD.69.072001 PACS number(s): 13.25.Gv, 12.38.Qk, 14.40.Gx

I. INTRODUCTION

In perturbative QCD, the J/ψ and $\psi(2S)$ decay branching fractions to the same final state are expected to satisfy [1]

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

where the leptonic branching fractions are taken from the Particle Data Group (PDG) tables [2]. This prediction is sometimes referred to as the "12% rule." Although it seems to work reasonably well for a number of specific decay

*Visiting professor to University of Michigan, Ann Arbor, MI 48109, USA.

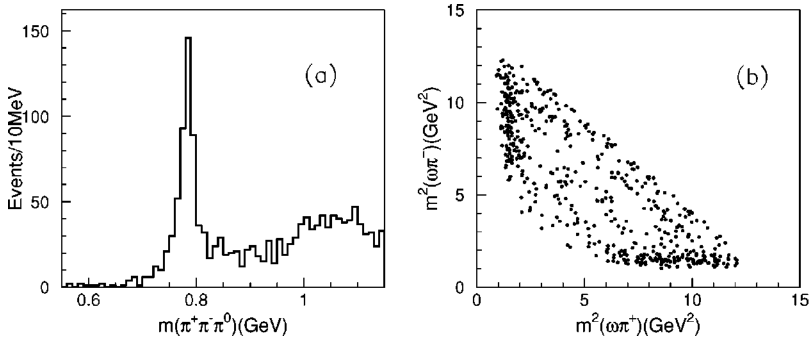

FIG. 1. Distributions of $\psi(2S)\to\omega\pi^+\pi^-$ candidate events: (a) the invariant mass of $\pi^+\pi^-\pi^0$, and (b) the Dalitz plot for $\omega\pi^+\pi^-$ events.

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 $K^*\bar{K}$, which is the well known "$\rho\pi$ puzzle" [3,4].

Previous BESI results [5,6] on vector-tensor meson [$\omega f_2(1270)$, $\rho a_2(1320)$, $K^*(892)^0\bar{K}_2^*(1430)^0$ + c.c., and $\phi f_2'(1525)$] final states reveal that these vector-tensor (VT) decay modes are also suppressed compared to the perturbative QCD prediction. However, the measurements, using about 4×10^6 $\psi(2S)$ events, determined only upper limits or branching fractions with large errors. Therefore it is hard to tell how strongly these decays are suppressed with respect to the 12% rule expectation. Here, we report the measurement of the branching fractions of $\psi(2S)$ decays into these four channels with higher precision, based on 14.0×10^6 (1.00 ± 0.04) $\psi(2S)$ events [7] taken with the upgraded BESII detector. The results improve on the previous BESI measurements and confirm the violation of the "12%" rule for $\psi(2S)$ decays to VT channels.

II. THE BESII DETECTOR

The Beijing Spectrometer (BESII) is a conventional cylindrical magnetic detector that is described in detail in Ref. [8]. A 12-layer vertex chamber (VC) surrounding the beryllium beam pipe provides input to the event trigger, as well as coordinate information. A 40-layer main drift chamber (MDC) located just outside the VC yields precise measurements of charged particle trajectories with a solid angle coverage of 85% of 4π; it also provides ionization energy loss (dE/dx) measurements which are used for particle identification. Momentum resolution of $1.7\%\sqrt{1+p^2}$ (p in GeV/c) and dE/dx resolution for hadron tracks of $\sim 8\%$ are obtained. An array of 48 scintillation counters surrounding the MDC measures the time of flight (TOF) of charged particles with a resolution of about 200 ps for hadrons. Outside the TOF counters, a 12 radiation length, lead-gas barrel shower counter (BSC), operating in limited streamer mode, measures the energies of electrons and photons over 80% of the total solid angle with an energy resolution of $\sigma_E/E=0.22/\sqrt{E}$ (E in GeV). A solenoidal magnet outside the BSC provides a 0.4 T magnetic field in the central tracking region of the detector. Three double-layer muon counters instrument the magnet flux return and serve to identify muons with momentum greater than 500 MeV/c. They cover 68% of the total solid angle.

In this analysis, a GEANT3 based Monte Carlo package (SIMBES) with detailed consideration of the detector performance (such as dead electronic channels) is used. The consistency between data and Monte Carlo has been carefully checked in many high purity physics channels, and the agreement is reasonable.

III. EVENT SELECTION

The data sample used for this analysis consists of 14 million $\psi(2S)$ events, collected with BESII at the center-of-mass energy $\sqrt{s}=M_{\psi(2S)}$. The decay channels investigated are $\psi(2S)\to\omega f_2(1270)\to\pi^+\pi^-\pi^+\pi^-\pi^0$, $\rho a_2(1320)\to\pi^+\pi^-\pi^+\pi^-\pi^0$, $K^*(892)^0\bar{K}_2^*(1430)^0$ + c.c. $\to\pi^+\pi^-K^+K^-$, and $\phi f_2'(1525)\to K^+K^-K^+K^-$. Candidate events are required to satisfy the following general selection criteria.

(i) The number of charged particles must be equal to 4 with net charge zero.

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

(iii) For each charged track in an event, the $\chi^2_{PID}(i)$ and its corresponding $\mathrm{Prob}_{PID}(i)$ values are calculated based on the dE/dx measurements in the MDC and the TOF measurements in the TOF system, where

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

$$\mathrm{Prob}_{PID}(i)=\mathrm{Prob}(\chi^2_{PID}(i),n^{df}_{PID}),$$

where $n^{df}_{PID}=2$ is the number of degrees of freedom in the $\chi^2_{PID}(i)$ determination and $\mathrm{Prob}_{PID}(i)$ signifies the probability of this track being of particle type i ($i=\pi/K/p$). For an event to be selected for any signal channel, each track must be consistent with the expected particle type (π or K) by requiring that its Prob_{PID} is greater than 0.01 or greater than those for any other assignment.

(iv) Energy-momentum conservation is used to provide a four-constraint or five-constraint (where the invariant mass of the two photons is also constrainted to the π^0 mass for events with a π^0) kinematic fit (χ^2_{kine}) for each event. To be selected for a candidate final state, the fit probability must be greater than 0.01.

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

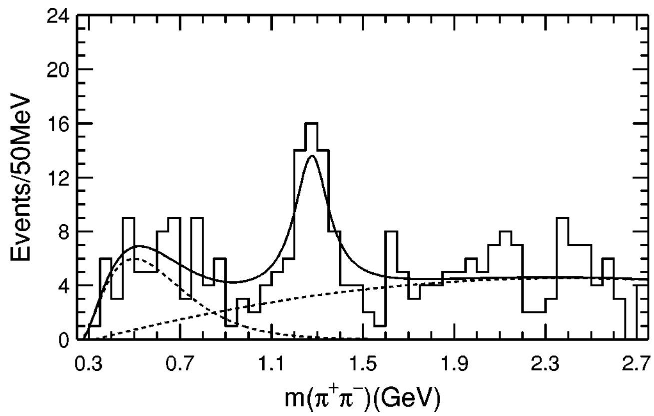

FIG. 2. $M_{\pi^+\pi^-}$ distribution of $\omega\pi^+\pi^-$ candidate events. The curves are the results of the fit discussed in the text.

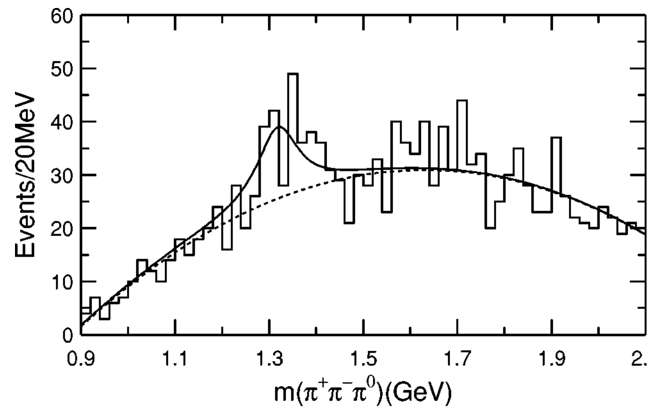

FIG. 3. Distribution of the $\rho\pi$ mass recoiling against another ρ. The curves are the best fit of the data.

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

which corresponds to the combined probability

$$\text{Prob}_{com} = \text{Prob}(\chi^2_{com}, n^{df}_{com}),$$

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

(vi) Backgrounds from $\psi(2S) \to \pi^+\pi^- J/\psi$, $J/\psi \to X$ are removed by the $\pi^+\pi^-$ pair recoiling mass requirement:

$$m^{\pi\pi}_{recoil} = \sqrt{(E_{c.m.} - E_+ - E_-)^2 - (\vec{p}_+ + \vec{p}_-)^2}$$

$$\notin (3.05, 3.15) \quad \text{GeV}/c^2,$$

where E_+ (E_-) and $\vec{p}_+$ ($\vec{p}_-$) are the π^+ (π^-) energy and momentum, respectively.

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

The candidate events for this decay mode have the final state $\pi^+\pi^-\pi^+\pi^-\pi^0$. To be selected, the combined probability (Prob_{com}) for the assignment $\psi(2S) \to \pi^+\pi^-\pi^+\pi^-\pi^0$ must be larger than those of $\psi(2S) \to \pi^+\pi^- K^+K^-\pi^0$ and $\psi(2S) \to \pi^+\pi^- p\bar{p}\pi^0$. A clear ω signal is seen in the $\pi^+\pi^-\pi^0$ mass distribution, as shown in Fig. 1(a), and candidate events are required to satisfy $|m_{\pi^+\pi^-\pi^0} - 0.783| < 0.05$ GeV/c^2. An additional requirement $|m_{\omega\pi^\pm} - 1.23| > 0.2$ GeV/c^2 removes almost all $b_1\pi$ events, which appear as vertical or horizontal bands in the Dalitz plot shown in Fig. 1(b).

After the above selection, a clear $f_2(1270)$ signal is seen in the $\pi^+\pi^-$ invariant mass distribution, as shown in Fig. 2, along with a smooth background and a broad enhancement at lower mass, which is attributed to σ [$f_0(400$–$1200)$] production [9]. Fitting with a Breit-Wigner function for the $f_2(1270)$ with mass and width fixed to its PDG values [2], plus a second order polynomial for background, and a σ, where its spectrum is obtained from J/ψ decays [9], 62 ± 12 signal events are obtained. The statistical significance for the $f_2(1270)$ signal is 6.0σ.

B. $\psi(2S) \to \rho a_2(1320)$

The $\pi^+\pi^-\pi^+\pi^-\pi^0$ final state is also used to search for $\psi(2S) \to \rho a_2(1320) \to \rho\rho\pi$ decay. Contamination from $\omega\pi^+\pi^-$ is eliminated by requiring $|m_{\pi^+\pi^-\pi^0} - 0.783| > 0.03$ GeV/c^2. We select the $\pi^+\pi^-$ and $\pi^0\pi^\pm$ combination that has the minimum value of $\sqrt{(m_{\pi^+\pi^-} - m_{\rho^0})^2 + (m_{\pi^0\pi^\pm} - m_{\rho^\pm})^2}$ and require this minimum value to be less than 200 MeV/c. The combined $\rho^0\pi^\pm$ and $\rho^\pm\pi^\mp$ invariant mass plot, shown in Fig. 3, has a clear peak near 1320 MeV/c. Assuming the signal is $a_2(1320)$, we obtain 112 ± 31 events by fitting the mass distribution with a Breit-Wigner function with mass and width fixed at the PDG values [2], together with a second order polynomial background function. The statistical significance is 3.6σ.

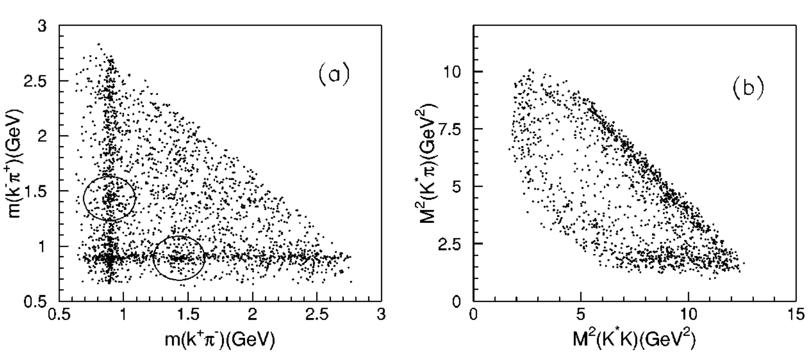

FIG. 4. Distributions of $\psi(2S) \to K^*(892)K^\pm\pi^\mp$ candidate events: (a) scatter plot of $m_{K^+\pi^-}$ versus $m_{K^-\pi^+}$ for selected $\psi(2S) \to \pi^+\pi^- K^+K^-$, and (b) Dalitz plot for $K^*(892)K\pi$ candidate events after $K^*(892)$ selection.

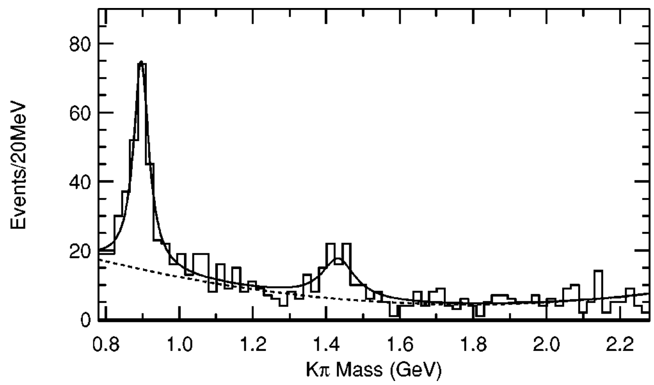

FIG. 5. Invariant mass of $K\pi$ for $\psi(2S) \to K^*(892)^0\bar{K}_2^*(1430)+\text{c.c.}$ events. The curves are the result of the fit described in the text.

C. $\psi(2S)\to K^*(892)^0\bar{K}_2^*(1430)^0+\text{c.c.}$

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 $K^+K^-K^+K^-$ and $\pi^+\pi^-\pi^+\pi^-$. The decay $\psi(2S) \to \phi\pi^+\pi^-$ is removed by the requirement $|m_{K^+K^-}-1.02| > 0.02$ GeV/c^2. Candidate $K^*(892)K^\pm\pi^\mp$ events are required to satisfy $|m_{K^\pm\pi^\mp}-0.896|<0.1$ GeV/c^2. The $K\pi$ mass distribution of these events is shown in Fig. 4(a). We require $m_{\pi^+\pi^-K^\pm}>1.6$ GeV/c^2 to remove the background from $K_1(1270)K$, which appears as a horizontal cluster in Fig. 4(b).

Figure 5 shows a clear peak near $m_{K\pi}=1430$ MeV/c. By fitting the $K\pi$ invariant mass distribution with two Breit-Wigner functions for the $K^*(892)^0$ and $K_2^*(1430)^0$ plus a second order polynomial background function, 93 ± 16 events are obtained with the signal statistical significance of 5.3σ.

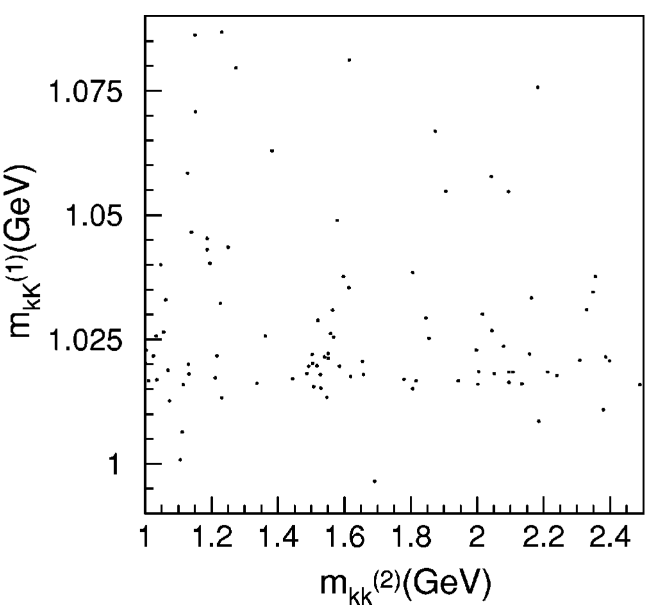

FIG. 6. Evidence for $\psi(2S)\to\phi f_2'(1525)$: scatter plot of $m^{(1)}_{K^+K^-}$ versus $m^{(2)}_{K^+K^-}$, where the $K^+K^{-(1)}$ pairs are assumed to be produced by a ϕ and $m^{(2)}_{K^+K^-}$ is the invariant mass recoiling against $K^+K^{-(1)}$. Each event has four entries.

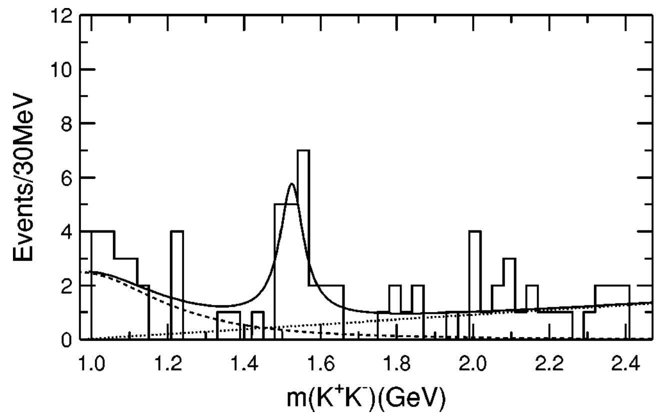

FIG. 7. Invariant mass distribution of K^+K^- recoiling against a ϕ for ϕK^+K^- events. The curves are the result of the fit described in the text.

D. $\psi(2S)\to\phi f_2'(1525)$

For this decay, the combined probability for $\psi(2S) \to K^+K^-K^+K^-$ is required to be larger than those of $K^+K^-\pi^+\pi^-$, $K^+K^-p\bar{p}$, and $\pi^+\pi^-\pi^+\pi^-$. Figure 6 shows clear evidence for $\psi(2S)\to\phi f_2'(1525)$.

Events containing a ϕ particle are selected with the additional requirement $|m_{K^+K^-}-1.02|<0.02$ GeV/c^2. By fitting the invariant mass $m_{K^+K^-}$ recoiling against a reconstructed ϕ particle with a Breit-Wigner function with the mass and width of the $f_2'(1525)$ fixed at its PDG values [2], plus a Flatté function for $f_0(980)$ [14] and a first order polynomial for background, as shown in Fig. 7, 19.7 ± 5.6 events are obtained. The statistical significance of the signal is 4.3σ.

A possible $\phi f_0(1500)$ state could also decay into $K^+K^-K^+K^-$, and since the width of $f_0(1500)$ is 109 MeV/c, it could contaminate the $\phi f_2'(1525)$ signal. However, the branching fraction of $f_0(1500)\to\pi\pi$ is three times larger than that of $f_0(1500)\to K\bar{K}$ [10], and an analysis of $\psi(2S)\to\phi f_0(1500)\to\phi\pi^+\pi^-$ finds no events from $\phi f_0(1500)$. Hence, the contamination from $\psi(2S) \to\phi K^+K^-$ is neglected.

TABLE I. Summary of systematic errors (%).

	ωf_2	ρa_2	$K^{*0}\bar{K}_2^{*0}+\text{c.c.}$	$\phi f_2'$
Tracking efficiency			8.0	
Kinematic fit	4.0	4.0	6.0	6.0
PID efficiency	3.2	3.2	4.0	6.0
γ selection	5.4	5.4	—	—
MC fluctuation	2.2	1.6	1.3	1.1
Helicity	8.1	1.2	14.3	16.0
Background shape	11.0	13.9	13.5	13.8
Branching fractions	2.9	3.4	2.4	3.8
$N_{\psi(2S)}$			4.0	
Sum	18.3	18.5	23.2	25.0

TABLE II. Branching fractions measured for $\psi(2S)\to$vector+tensor. Results for corresponding J/ψ branching fractions [13] are also given as well as the ratio $Q_X = B(\psi(2S)\to X)/B(J/\psi\to X)$.

X	N^{obs}	ϵ (%)	$B(\psi(2S)\to X)$ ($\times 10^{-4}$)	$B(J/\psi\to X)$ ($\times 10^{-3}$)	Q_X (%)
ωf_2	62 ± 12	4.25 ± 0.10	$2.05\pm 0.41\pm 0.38$	4.3 ± 0.6	4.8 ± 1.5
ρa_2	112 ± 31	6.42 ± 0.06	$2.55\pm 0.73\pm 0.47$	10.9 ± 2.2	2.3 ± 1.1
$K^*\bar{K}_2^*$	93 ± 16	16.2 ± 0.2	$1.86\pm 0.32\pm 0.43$	6.7 ± 2.6	2.8 ± 1.3
$\phi f_2'$	19.7 ± 5.6	14.8 ± 0.2	$0.44\pm 0.12\pm 0.11$	1.23 ± 0.21	3.6 ± 1.5

IV. SYSTEMATIC ERRORS

The branching fraction for $\psi(2S)\to X$ is calculated from

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

where X is the intermediate state, Y the final state, and ϵ^{MC} the detection efficiency. Many sources of systematic error are considered. Systematic errors associated with the efficiency are determined by comparing J/ψ and $\psi(2S)$ data and Monte Carlo (MC) simulation for very clean decay channels, such as $\psi(2S)\to\pi^+\pi^- J/\psi$, which allows the determination of systematic errors associated with the MDC tracking efficiency, kinematic fitting, particle identification, and photon selection efficiency [11].

Another source of systematic error comes from uncertainties in the angular distributions used in the simulation. Events are generated according to the helicity amplitudes allowed by the spin and parity of the particles in the decay chain. However, the limited statistics does not allow a determination of the helicity amplitudes. This uncertainty is considered as another source of systematic error.

Contributions from the continuum $e^+e^-\to\gamma^*\to$ hadrons [12] are estimated using a data sample of $\sim$6.0 pb^{-1} taken at $\sqrt{s}=3.65$ GeV/c^2, about one-third of the integrated luminosity at the $\psi(2S)$. No signal is found for any channel under study, hence this background is neglected. The uncertainties of the branching fractions of intermediate states, the background shapes, and the total number of $\psi(2S)$ events are also sources of systematic errors. Table I summarizes the systematic errors for all channels; the total branching fraction errors for ωf_2, ρa_2, $K^{*0}\bar{K}_2^{*0}$+c.c., and $\phi f_2'$ are 18.3%, 18.5%, 23.2%, and 25.0%, respectively.

V. RESULTS

Table II summarizes the results of the four branching fraction measurements. For comparison, the table includes the corresponding decay branching fractions of J/ψ decays [13], as well as the ratios of the $\psi(2S)$ to J/ψ branching fractions. These results have smaller statistical errors than the previous BESI measurements, mainly due to the larger $\psi(2S)$ event sample. The statistical significances for all four channels are larger than 3σ; those for $\omega f_2(1270)$ and $K^*(892)^0\bar{K}^*(1430)^0$+c.c. are larger than 5σ.

In perturbative QCD, VP decays are forbidden by hadron helicity conservation (HHC) [15], whereas VT decay are HHC allowed [16]. Although the suppression of the VT decays is not as severe as that of the $\rho\pi$ and $K^*\bar{K}$ decay channels, all four VT decay modes are suppressed by a factor of 3 to 5 compared with the perturbative QCD expectation.

ACKNOWLEDGMENTS

The BES Collaboration thanks the staff of BEPC for their hard effort. This work was supported in part by the National Natural Science Foundation of China under Contract Nos. 19991480, 10225524, and 10225525, the Chinese Academy of Sciences under Contract No. KJ 95T-03, the 100 Talents Program of CAS under Contract Nos. U-11, U-24, U-25, and the Knowledge Innovation Project of CAS under Contract Nos. U-602 and U-34 (IHEP); by the National Natural Science Foundation of China under Contract No. 10175060 (USTC); and by the Department of Energy under Contract No. DE-FG03-94ER40833 (U. Hawaii).

[1] W.S. Hou and A. Soni, Phys. Rev. Lett. **50**, 569 (1983); G. Karl and W. Roberts, Phys. Lett. **144B**, 243 (1984); S.J. Brodsky *et al.*, Phys. Rev. Lett. **59**, 621 (1987); M. Chaichian *et al.*, Nucl. Phys. **B323**, 75 (1989); S.S. Pinsky, Phys. Lett. B **236**, 479 (1990); X.Q. Li *et al.*, Phys. Rev. D **55**, 1421 (1997); S.J. Brodsky and M. Karliner, Phys. Rev. Lett. **78**, 4682 (1997); Yu-Qi Chen and Eric Braaten, *ibid.* **80**, 5060 (1998); M. Suzuki, Phys. Rev. D **63**, 054021 (2001); J.L. Rosner, *ibid.* **64**, 094002 (2001); J.P. Ma, *ibid.* **65**, 097506 (2002); M. Suzuki, *ibid.* **65**, 097507 (2002).

[2] Particle Data Group, K. Hagiwara *et al.*, Phys. Rev. D **66**, 010001 (2002).

[3] MARK II Collaboration, M.E.B. Franklin *et al.*, Phys. Rev. Lett. **51**, 963 (1983).

[4] BES Collaboration, Y.S. Zhu, in *Proceedings of the 28th International Conference on High Energy Physics*, edited by Z. Adjuk and A.K. Wroblewski (World Scientific, Singapore, 1997), p. 507.

[5] BES Collaboration, J.Z. Bai *et al.*, Phys. Rev. Lett. **81**, 5080 (1998).

[6] BES Collaboration, J.Z. Bai *et al.*, Phys. Rev. D **67**, 052002 (1981).

[7] X.H. Mo *et al.*, ‘‘Determination of $\psi(2S)$ Total Number by Inclusive Hadronic Decay,’’ High Energy Phys. Nucl. Phys. (to be published).

[8] BES Collaboration, J.Z. Bai *et al.*, Nucl. Instrum. Methods Phys. Res. A **458**, 627 (2001).

[9] BES Collaboration, W.G. Li, ‘‘Recent BES Results,’’ X International Conference On Hadron Spectroscopy, Aschaffenburg, Germany, 2003.

[10] A. Kirk, Nucl. Phys. **A663**, 608c (2000).

[11] See the deteremination of systematic errors in BES Collaboration, J.Z. Bai *et al.*, Phys. Rev. D **69**, 012003 (2004).

[12] P. Wang, C.Z. Yuan, and X.H. Mo, High Energy Phys. Nucl. Phys. **27**, 465 (2003); hep-ph/0303144; P. Wang *et al.*, hep-ex/0210063; P. Wang, X.H. Mo, and C.Z. Yuan, Phys. Lett. B **557**, 192 (2003); C.Z. Yuan, P. Wang, and X.H. Mo, *ibid.* **567**, 73 (2003).

[13] For the first three decays, we use the PDG recommended values of the J/ψ branching fractions. For J/ψ decay to $\phi f_2'$, there is poor consistency between the existing measurement, Mark II, and DM2. Instead of the PDG average with 50% error, we use the data of DM2, which was a high statistics measurement, giving smaller errors and including the interference with $f_0(1710)$.

[14] S.M. Flatté, Phys. Lett. **63B**, 224 (1976); B.S. Zou and D.V. Bugg, Phys. Rev. D **48**, 3948 (1993).

[15] S.J. Brodsky and G.P. Lepage, Phys. Rev. D **24**, 2848 (1981).

[16] Y.F. Gu and S.F. Tuan, Mod. Phys. Lett. A **10**, 615 (1995).