$\psi(2S)$ Hadronic Decays to Vector- Tensor Final States

J. Z. Bai[1], J. G. Bian[1], I. Blum[11], Z. W. Chai[1], G. P. Chen[1], H. F. Chen[10], J. Chen[3], J. C. Chen[1], Y. Chen[1], Y. B. Chen[1], Y. Q. Chen[1], B. S. Cheng[1] X. Z. Cui[1], H. L. Ding[1], L. Y. Ding[1], L. Y. Dong[1], Z. Z. Du[1], W. Dunwoodie[7], S. Feng[1], C. S. Gao[1], M. L. Gao[1], S. Q. Gao[1], P. Gratton[11], J. H. Gu[1], S. D. Gu[1], W. X. Gu[1], Y. F. Gu[1], Y. N. Guo[1], S. W. Han[1], Y. Han[1], F. A. Harris[8], J. He[1], J. T. He[1], M. He[5], D. G. Hitlin[2], G. Y. Hu[1], H. M. Hu[1], J. L. Hu[1], Q. H. Hu[1], T. Hu[1], X. Q. Hu[1], J. D. Huang[1], Y. Z. Huang[1], J. M. Izen[11], C. H. Jiang[1], Y. Jin[1], Z. J. Ke[1], M. H. Kelsey[2], B. K. Kim[11], D. Kong[8], Y. F. Lai[1], P. F. Lang[1], A. Lankford[9], C. G. Li[1], D. Li[1], H. B. Li[1], J. Li[1], P. Q. Li[1], R. B. Li[1], W. Li[1], W. D. Li[1], W. G. Li[1], X. H. Li[1], X. N. Li[1], H. M. Liu[1], J. Liu[1], J. H. Liu[1], R. G. Liu[1], Y. Liu[1], X. C. Lou[11], B. Lowery[11], F. Lu[1], J. G. Lu[1], J. Y. Lu[1], L. C. Lu[1], C. H. Luo[1], A .M .Ma[1], E. C. Ma[1], J. M. Ma[1], R. Malchow[3], H. S. Mao[1], Z. P. Mao[1], X. C. Meng[1], J. Nie[1], S. L. Olsen[8], J. Oyang[2], D. Paluselli[8], L. J. Pan[8], J. Panetta[2], F. Porter[2], N. D. Qi[1], X. R. Qi[1], C. D. Qian[6], J. F. Qiu[1], Y. H. Qu[1], Y. K. Que[1], G. Rong[1], M. Schernau[9], Y. Y. Shao[1], B. W. Shen[1], D. L. Shen[1], H. Shen[1], X. Y. Shen[1], H. Y. Sheng[1], H. Z. Shi[1], X. F. Song[1], J. Standifird[11], F. Sun[1], H. S. Sun[1], S. Q. Tang[1], W. Toki[3], G. L. Tong[1], F. Wang[1], L. S. Wang[1], L. Z. Wang[1], M. Wang[1], Meng Wang[1], P. Wang[1], P. L. Wang[1], S. M. Wang[1], T. J. Wang[1][†], Y. Y. Wang[1], M. Weaver[2], C. L. Wei[1], Y. G. Wu[1], D. M. Xi[1], X. M. Xia[1], P. P. Xie[1], Y. Xie[1], Y. H. Xie[1], W. J. Xiong[1], C. C. Xu[1], G. F. Xu[1], S. T. Xue[1], J. Yan[1], W. G. Yan[1], C. M. Yang[1], C. Y. Yang[1], J. Yang[1], W. Yang[3], X. F. Yang[1], M. H. Ye[1], S. W. Ye[10], Y. X. Ye[10], K. Yi [1], C. S. Yu[1], C. X. Yu[1], Y. H. Yu[4], Z. Q. Yu[1], Z. T. Yu[1], C. Z. Yuan[1], Y. Yuan[1], B. Y. Zhang[1], C. C. Zhang[1], D. H. Zhang[1], Dehong Zhang[1], H. L. Zhang[1], J. Zhang[1], J. L. Zhang[1], J. W. Zhang[1], L. S. Zhang[1], Q. J. Zhang[1], S. Q. Zhang[1], X. Y. Zhang[5], Y. Zhang[1], Y. Y. Zhang[1], D. X. Zhao[1], H. W. Zhao[1], J. W. Zhao[1], M. Zhao[1], W. R. Zhao[1], Z. G. Zhao[1], J. P. Zheng[1], L. S. Zheng[1], Z. P. Zheng[1], G. P. Zhou[1], H. S. Zhou[1], L. Zhou[1], Q. M. Zhu[1], Y. C. Zhu[1], Y. S. Zhu[1], B. A. Zhuang[1]
(BES Collaboration)
[1] *Institute of High Energy Physics, Beijing 100039, People's Republic of China*
[2] *California Institute of Technology, Pasadena, California 91125*
[3] *Colorado State University, Fort Collins, Colorado 80523*
[4] *Hangzhou University, Hangzhou 310028, People's Republic of China*
[5] *Shandong University, Jinan 250100, People's Republic of China*
[6] *Shanghai Jiaotong University, Shanghai 200030, People's Republic of China*
[7] *Stanford Linear Accelerator Center, Stanford, California 94309*
[8] *University of Hawaii, Honolulu, Hawaii 96822*
[9] *University of California at Irvine, Irvine, California 92717*
[10] *University of Science and Technology of China, Hefei 230026, People's Republic of China*
[11] *University of Texas at Dallas, Richardson, Texas 75083-0688*

(December 5, 1998)

The decays of the $\psi(2S)$ into vector plus tensor meson final states have been studied for the first time using the BES detector. We determine upper limits on branching fractions for $\psi(2S)$ decays into ωf_2, ρa_2, $K^{*0}\overline{K_2^{*0}}$+*c.c.*, and $\phi f_2'(1525)$ that are, in each case, significantly smaller than the corresponding branching fractions for the J/ψ meson, scaled according to expectations of perturbative QCD.

PACS numbers: 13.25.Gv, 12.38.Qk

One of the most dramatic problems confronting the understanding of hadronic charmonium decays is the strong suppression of $\psi(2S) \to \rho\pi$ and $K^*\overline{K} + c.c.$ decays. In perturbative QCD, the most important lowest-order diagram for J/ψ and $\psi(2S)$ decays to hadrons corresponds to the annihilation of the constituent c and $\bar{c}$ quarks into three gluons. In this case, the partial width for the decay is proportional to $\mid \Psi(0) \mid^2$, where $\Psi(0)$ is the wave function at the origin in the nonrelativistic quark model for $c\bar{c}$. Thus, it is reasonable to expect that for any final hadronic state h, the J/ψ and $\psi(2S)$ decay branching ratios will scale as [1]

$$Q_h \equiv \frac{B(\psi(2S) \to h)}{B(J/\psi \to h)} \cong \frac{B(\psi(2S) \to e^+e^-)}{B(J/\psi \to e^+e^-)} \tag{1}$$
$$= (14.6 \pm 2.2)\%,$$

where the leptonic branching fractions are taken from the PDG tables [2]. It was first observed by the Mark II experiment [3] that, while this is true for a number of exclusive hadronic decay channels, it is badly violated for the vector plus pseudoscalar meson (VP) final states, $\rho\pi$ and $K^*\overline{K}$. The preliminary BES results confirm the Mark II measurements at higher sensitivity. The present experimental limits on $Q_{\rho\pi}$ and $Q_{K^*\overline{K}}$ indicate order-of-magnitude discrepancies with the expected ratio of branching fractions [2, 4]. This anomaly, called the $\rho\pi$ puzzle, has generated considerable interest, and a number of theoretical explanations have been proposed [1].

However, meager experimental progress has hindered the resolution of the puzzle. Until recently, no other examples of substantial differences between J/ψ and $\psi(2S)$ hadronic decays have been documented.

In this letter, we report the results of a study of $\psi(2S)$ decays into vector plus tensor meson (VT) final states and present branching fraction limits for $\psi(2S) \to \omega f_2$, ρa_2, $K^{*0}\overline{K_2^{*0}} + c.c.$, and $\phi f_2'(1525)$. The data were taken with the BES detector at the BEPC e^+e^- storage ring and correspond to a total sample of $(3.79 \pm 0.31) \times 10^6$ produced $\psi(2S)$ events. The BES detector is described in detail elsewhere [5]. A 40-layer main drift chamber in a 0.4 Tesla magnetic field provides tracking and energy-loss (dE/dx) information. The momentum resolution is $\sigma_p/p = 1.7\%\sqrt{1+p^2(GeV/c)}$, and the dE/dx resolution for hadron tracks for this data sample is about 9%. The tracking chamber is surrounded by an array of 48 time-of-flight (TOF) counters with resolution of about 450 ps for hadrons. Radially outside of the TOF are an electromagnetic calorimeter with resolution $\sigma_E/E = 0.22/\sqrt{E(GeV)}$, $\sigma_\phi = 4.5$ mrad, and $\sigma_\theta = 12$ mrad, and an array of μ counters that are interspersed inside the steel plates that return the solenoid's magnetic flux.

For the $\psi(2S) \to \omega f_2$ and ρa_2 decay channels, we use the reaction $\psi(2S) \to \pi^+\pi^-\pi^+\pi^-\pi^0$; for the $\psi(2S) \to K^{*0}\overline{K_2^{*0}}$ + c.c. and $\phi f_2'$ decays, we use $\pi^+\pi^-K^+K^-$ and $K^+K^-K^+K^-$ final states, respectively. Each analysis requires events to have four charged tracks with total charge zero and, in the case of the $\pi^+\pi^-\pi^+\pi^-\pi^0$ final state, at least two photons. Tracks consistent with being electrons in the electromagnetic calorimeter or being muons in the muon detector are discarded. The dE/dx and TOF measurements are used to select π or K tracks with confidence level larger than 0.003 for each track and 0.01 for four tracks combined. Events are kinematically fit to four energy-momentum constraints, and those with a fit probability greater than 0.01 are accepted. Photon pairs that have a $\gamma\gamma$ invariant mass within 2.5σ ($\sigma = 14$ MeV) of the π^0 mass are assigned as candidate π^0s. The detection efficiency is determined using 1 or 2 $\times 10^4$ MC-simulated events that are generated with a uniform phase space distribution. The π or K decays in the detector according to the PDG [2] life times and branching fractions. The relative uncertainty of efficiency obtained in this way is estimated to be 20%. Efficiencies given in this paper refer to the specific VT final states.

In the $\pi^+\pi^-\pi^+\pi^-\pi^0$ sample, the major background contributions are from $\psi(2S) \to \pi^+\pi^-J/\psi$ followed by $J/\psi \to \pi^+\pi^-\pi^0$ and from $\psi(2S) \to \eta J/\psi$, where $\eta \to \pi^+\pi^-\pi^0$ and the J/ψ decays to leptons. The former is rejected by removing events where any $\pi^+\pi^-\pi^0$ combination has an invariant mass within 50 MeV of the J/ψ mass. The latter is removed by eliminating events where any $\pi^+\pi^-$ pair has an invariant mass greater than 2.9 GeV/c^2. There are 939 events selected as $\psi(2S) \to \pi^+\pi^-\pi^+\pi^-\pi^0$ candidate events. The $\pi^+\pi^-\pi^0$ mass spectrum of the selected events, shown in Fig. 1, has a clear ω signal with a mass resolution $\sigma = 13.4$ MeV. Candidate ω mesons are required to have a $\pi^+\pi^-\pi^0$ combination with an invariant mass in the range $740 < m_{\pi^+\pi^-\pi^0} < 820$ MeV. Figure 2 shows the invariant mass spectrum for $\pi^+\pi^-$ pairs recoiling against candidate ω mesons. There is no obvious signal in the region of the $f_2(1270)$. A fit to the spectrum using a Breit-Wigner function with mass and width fixed at the PDG values (m=1275 MeV, Γ=185 MeV) and convoluted with a Gaussian resolution function with $\sigma = 12.3$ MeV, together with a quadratic background shape, yields 8.8 ± 9.2 ωf_2 events, which imply a 90% confidence level upper limit of 23.8 events. Using the isospin ratio 2:1 for f_2 decays into $\pi^+\pi^-$ to $\pi^0\pi^0$ and the experimental efficiency of 0.074, we determine an upper limit on the branching fraction of

$$B(\psi(2S) \to \omega f_2) < 1.7 \times 10^{-4} \qquad (C.L. = 90\%).$$

We use the $\psi(2S) \to \pi^+\pi^-\pi^+\pi^-\pi^0$ sample with the events that are consistent with $\omega\pi^+\pi^-$ removed to search for $\psi(2S) \to \rho a_2 \to \rho\rho\pi$. Here we select the $\pi^+\pi^-$ and $\pi^0\pi^\pm$ combination that has the minimum value of the quantity [6]

$$\sqrt{(m_{\pi^+\pi^-} - m_{\rho^0})^2 + (m_{\pi^0\pi^\pm} - m_{\rho^\pm})^2}$$

and require this minimum value to be less than 200 MeV. The combined $\rho^0\pi^\pm$ and $\rho^\pm\pi^\mp$ invariant mass plot, shown in Fig. 3, has no indication of an $a_2(1320)$ meson signal. A fit to this spectrum with the a_2 represented by a resolution-broadened Breit-Wigner line shape with mass and width fixed at PDG values [2] (m=1318.1 MeV, Γ=107 MeV) and a quadratic background function gives 3.9 ± 15.7 a_2 events, which correspond to less than 29.6 events at the 90% confidence level. Using isospin invariance to correct for the unseen $a_2 \to \rho\pi$ decay channels and the MC-determined experimental efficiency of 0.074, we determine

$$B(\psi(2S) \to \rho a_2) < 2.3 \times 10^{-4} \qquad (C.L. = 90\%).$$

In the selection of $\pi^+\pi^-K^+K^-$ final states, each event has four possible π^+, π^-, K^+ and K^- track assignments. For each assignment that satisfies the four-constraint kinematic fit with a probability greater that 0.01, the TOF and dE/dx measurements and the kinematic fit quality are combined to determine a global χ^2. The track assignment with the smallest global χ^2 is selected as a candidate $\pi^+\pi^-K^+K^-$ event. The main background which remains from $\psi(2S) \to \pi^+\pi^-J/\psi$ is eliminated by requiring the mass recoiling against the $\pi^+\pi^-$ to differ from $m_{J/\psi}$ by more than 50 MeV. There are 614 events after the above selections. Those $K^\pm\pi^\mp$ pairs with an invariant mass in the range $800 < m_{K^\pm\pi^\mp} < 1000$ MeV are considered to be K^{*0} candidates. The contamination from $\psi(2S) \to \phi\pi^+\pi^-$ with $\phi \to K^+K^-$ is found to be negligible. The $K^\pm\pi^\mp$ mass spectrum, shown in Fig. 4, has a pronounced peak at the mass of the K^{*0}. The invariant mass distribution of $K^\pm\pi^\mp$ tracks recoiling against the K^{*0} candidates, shown in Fig. 5, is fit with two Breit-Wigner functions with masses and widths fixed at the PDG values for the K^{*0} (m=896.1 MeV, Γ=50.5 MeV) and K_2^{*0} (m=1432.4 MeV, Γ=109 MeV), together with a quadratic background. The MC-determined experimental mass resolutions are 4.9 MeV for the K^{*0} and 6.7 MeV for the K_2^{*0}. The fit yields 1.4 ± 8.6 $K^{*0}K_2^{*0}$ events, which imply a 90% confidence level upper limit of 17.2 events. Using the isospin ratio $K^\pm\pi^\mp : K^0\pi^0 = 2 : 1$ for both the K^{*0} and K_2^{*0} decays and the MC-determined efficiency of 0.171, we determine the limit

$$B(\psi(2S) \to K^{*0}\overline{K_2^{*0}} + c.c.) < 1.2 \times 10^{-4} \quad (C.L. = 90\%).$$

In the selection of $K^+K^-K^+K^-$ final states, the TOF and dE/dx measurements are used to select kaon tracks. Events are kinematically fit to four energy-momentum constraints, and those with a fit probability greater than 0.01 are accepted. Backgrounds from other $\psi(2S)$ decays are negligible. Figure 6 shows the K^+K^- mass spectrum for the 41 selected $K^+K^-K^+K^-$ candidate events; there is a strong $\phi(1020)$ signal. Here the experimental mass resolution is $\sigma = 4.1$ MeV. We identify all K^+K^- pairs with $m_{K^+K^-} < 1040$ MeV as candidate ϕ mesons. Figure 7 shows the invariant mass distribution for the K^+K^- pairs that are recoiling against candidate ϕ mesons. No evidence for an enhancement at the mass of the f_2' resonance is apparent. There are three events in the Fig. 7 distribution within ± 80 MeV of the f_2' mass (m=1525 MeV, Γ=76 MeV). The 90% confidenc levele upper limit on this number of events is 6.68. Using the MC-determined efficiency of 0.181, we determine an upper limit for the branching fraction of

$$B(\psi(2S) \to \phi f_2'(1525)) < 4.5 \times 10^{-5} \qquad (C.L. = 90\%).$$

Table I summarizes the results of branching fraction measurements for the $\psi(2S) \to VT$ decay modes reported here. For comparison, the table includes the data for the corresponding J/ψ decays [7] as well as the ratios of the $\psi(2S)$ to J/ψ branching fractions. All four $\psi(2S) \to VT$ decay modes are suppressed by a factor of at least three compared to the expectations of Eqn. 1. An even higher statistics study would be required to determine whether or not the suppression of the VT decays is as severe as that of the $\rho\pi$ and $K^*\overline{K}$ decay channels. It is noted that, in a perturbative QCD quark scheme, VP decays are forbidden by Hadron Helicity Conservation (HHC) [8], whereas VT decays are HHC allowed [9].

In conclusion, we have presented first measurements of $\psi(2S)$ decays to ωf_2, ρa_2, $K^{*0}\overline{K_2^{*0}}$, and $\phi f_2'(1525)$. The upper limits established for the branching fractions for each of these decay modes are well below the level obtained by scaling the corresponding J/ψ branching fraction according to expectations based on perturbative QCD. The puzzle of the hadronic decays of the J/ψ and $\psi(2S)$ extends from the VP decay to the VT decays.

We gratefully acknowledge the efforts of staffs of the BEPC accelerator and the computing center at the Institute of High Energy Physics (Beijing). The authors also wish to thank G. D. Zhao, S. J. Brodsky and S. F. Tuan for enlightening discussions.

[†] Deceased.

[*] Work supported in part by the National Natural Science Foundation of China under Contract No. 19290400 and the Chinese Academy of Sciences under Contract No. KJ85 (IHEP), and by the Department of Energy under Contract Nos. DE-FG03-92ER40701 (Caltech), DE-FG03-93ER40788 (Colorado State University), DE-AC03-76SF00515 (SLAC), DE-FG03-91ER40679 (UC Irvine), DE-FG03-94ER40833 (U Hawaii), DE-FG03-95ER40925 (UT Dallas).

[1] W.S.Hou and A.Soni, Phys. Rev. Lett. **50**, 569 (1983); G.Karl and W.Roberts, Phys. Lett. B **144**, 243 (1984); S.J.Brodsky et al., Phys. Rev. Lett. **59**, 631 (1987); M.Chaichian et al., Nucl. Phys. B **323**, 75 (1989); S.S.Pinsky, Phys. Lett. B **236**, 479 (1990); X.Q.Li et al., Phys. Rev. D **55**, 1241 (1997); S.J.Brodsky and M.Karliner, Phys. Rev. Lett. **78**, 468 (1997); Yu-Qi Chen and Eric Braaten, Phys. Rev. Lett. **80**, 5060 (1998).

[2] Particle Data Group, R.M.Barnett et al., Phys. Rev. D **54**, 1 (1996).

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

[4] BES Collab., J.Z.Bai et al., Phys. Rev. D **54**, 1221 (1996); Erratum: *ibid.* **57**, 3187 (1998).

[5] BES Collab., J.Z.Bai et al., Nucl. Instr. Methods A **344**, 319 (1994).

[6] DM2 Collab., J.E.Augustin et al., Nucl. Phys. B **320**, 1. (1989).

[7] For the first three decays, we use the PDG [2] recommended values of the J/ψ branching fractions. For J/ψ decay to $\phi f_2'$, there is poor consistency between the two existing measurements, MARK II and DM2 [2]. Instead of the PDG average with 50% error, we use the more recent data of DM2, which was a high statistics measurement, giving smaller errors and including the interference with $f_J(1710)$.

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

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

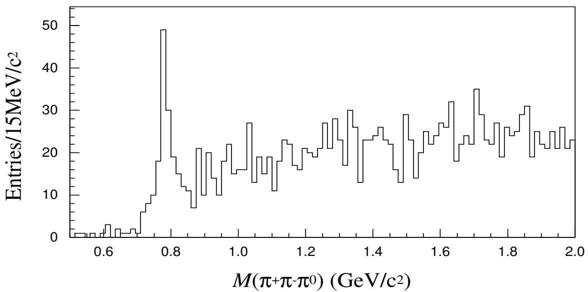

FIG. 1. The $\pi^+\pi^-\pi^0$ invariant mass distribution for $\psi(2S) \to \pi^+\pi^-\pi^+\pi^-\pi^0$ events (4 entries/event).

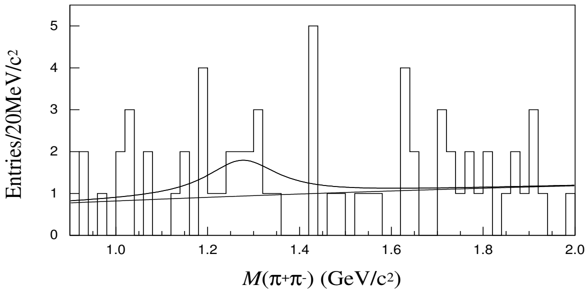

FIG. 2. The invariant mass distribution of $\pi^+\pi^-$ pairs recoiling against candidate ω mesons for events of the type $\psi(2S) \to \omega\pi^+\pi^-$. The curve shows a fit to quadratic background plus f_2 resonance (see text).

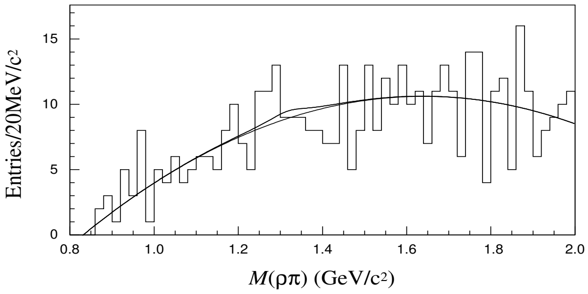

FIG. 3. The $\rho\pi$ invariant mass distribution for events of the type $\psi(2S) \to \rho^0\rho^\mp\pi^\pm$. The curve shows a fit to quadratic background plus an a_2 resonance (see text).

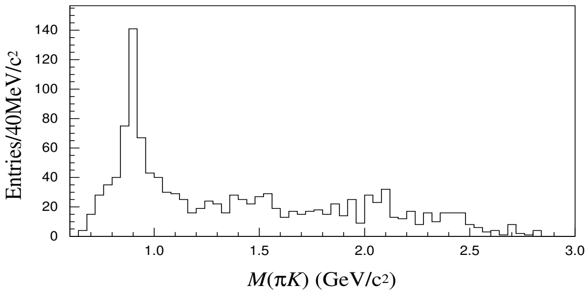

FIG. 4. The $\pi^\pm K^\mp$ invariant mass distribution for $\psi(2S) \to \pi^+\pi^- K^+K^-$ events (4 entries/event).

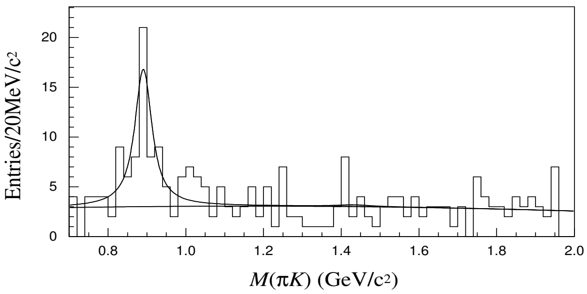

FIG. 5. The invariant mass distribution for $\pi^\pm K^\mp$ tracks recoiling against a K^{*0} for $\psi(2S) \to \pi^+\pi^- K^+K^-$ events. The curve shows a fit to quadratic background plus K^{*0} and K_2^{*0} resonances (see text).

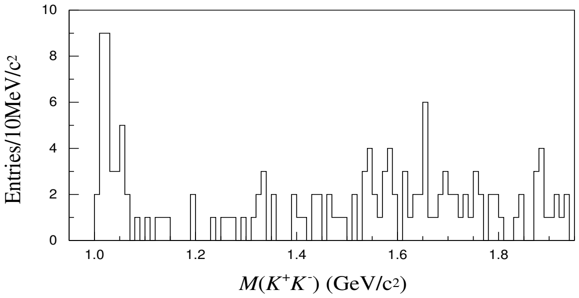

FIG. 6. The K^+K^- invariant mass distribution for $\psi(2S) \to K^+K^-K^+K^-$ events (4 entries/event).

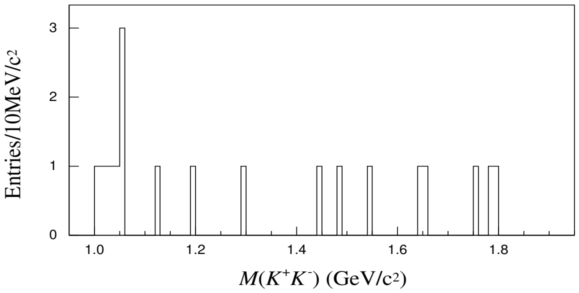

FIG. 7. The invariant mass distribution of K^+K^- pairs recoiling against candidate ϕ mesons for $\psi(2S) \to K^+K^-K^+K^-$ events. Three events fall into 80 MeV/c^2 region around the f_2' mass.

Table I. Branching fractions measured for $\psi(2S) \to$ vector plus tensor meson final states. Results for the corresponding J/ψ branching fractions [7] are also given as well as the ratios $Q_h \equiv B(\psi(2S))/B(J/\psi)$. All limits are at the 90% confidence level.

Final state	$B(\psi(2S))$ ($\times 10^{-4}$)	$B(J/\psi)$ ($\times 10^{-3}$)	Q_h
ωf_2	< 1.7	4.3 ± 0.6	< 0.040
ρa_2	< 2.3	10.9 ± 2.2	< 0.021
$K^{*0}\overline{K_2^{*0}}$	< 1.2	6.7 ± 2.6	< 0.018
$\phi f_2'$	< 0.45	$1.23 \pm 0.06 \pm 0.20$	< 0.037