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

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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 expections of perturbative QCD.

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]

$$Q_h \equiv \frac{B(\psi(2S) \to h)}{B(J/\psi \to h)} \cong \frac{B(\psi(2S) \to e^+e^-)}{B(J/\psi \to e^+e^-)} \qquad (1)$$

$$= (14.6 \pm 2.2)\%,$$

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 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]. 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 million produced $\psi(2S)$ events. The BES detector is described in detail elsewhere [4]. Charged particles are tracked using a 40-layer cylindrical drift chamber in a 0.4 Tesla magnetic field with a momentum resolution $\sigma_p/p = 1.7\%\sqrt{1+p^2(GeV/c)}$. 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. Ionization measurements in the drift chamber and the TOF counter times are used to calculate probablities in order to test whether each charged track is consistent with the pion or kaon hypothesis. Tracks consistent with being electrons in the electromagnetic calorimeter or being muons in the muon detector are discarded. 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 MC-simulated events that are generated with a uniform phase space distribution.

In the $\pi^+\pi^-\pi^+\pi^-\pi^0$ sample, there is a background contribution from $\psi(2S) \to \eta J/\psi$, where $\eta \to \pi^+\pi^-\pi^0$ and the J/ψ decays to leptons. This is removed by eliminating events where any $\pi^+\pi^-$ pair has an invariant mass greater than 2.9 GeV/c^2. Contamination from $\psi(2S) \to \pi^+\pi^- J/\psi$ followed by $J/\psi \to \pi^+\pi^-\pi^0$ 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 $\pi^+\pi^-\pi^0$ 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 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 [5]

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

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] 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 remaining backgrounds from $\psi(2S) \to \pi^+\pi^- J/\psi$ are eliminated by requiring the mass recoiling against the $\pi^+\pi^-$ to differ from $m_{J/\psi}$ by more than 50 MeV. 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} and K_2^{*0}, 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

$$B(\psi(2S) \to K^{*0}\overline{K_2^{*0}} + c.c.) < 1.2\times10^{-4} \quad (C.L. = 90\%).$$

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. The 90% confidence 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

$$B(\psi(2S) \to \phi f_2'(1525)) < 4.5\times10^{-5} \qquad (C.L. = 90\%).$$

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 [6] 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) [7], whereas VT decays are HHC allowed [8].

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.

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[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., Nucl. Instr. Methods A **344**, 319 (1994).

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

[6] 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 $f_J(1710)$.

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

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

Table I. Branching fractions measured for $\psi(2S) \to$ vector plus tensor-meson final states. Results for the corresponding J/ψ branching fractions [6] 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	$B(\psi(2S))$ $(\times10^{-4})$	$B(J/\psi)$ $(\times10^{-3})$	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

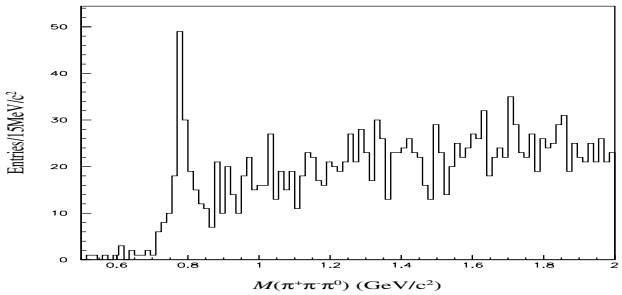

FIG. 1. The $\pi^+\pi^-\pi^0$ invariant mass distribution for $\psi(2S) \to \pi^+\pi^-\pi^+\pi^-\pi^0$ events (4 entries/event).

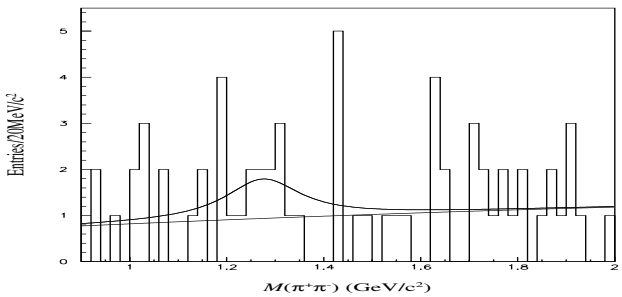

FIG. 2. The invariant mass distribution of $\pi^+\pi^-$ pairs recoiling against candidate ω mesons for events of the type $\psi(2S) \to \omega\pi^+\pi^-$. The curve shows a fit to quadratic background plus f_2 resonance (see text).

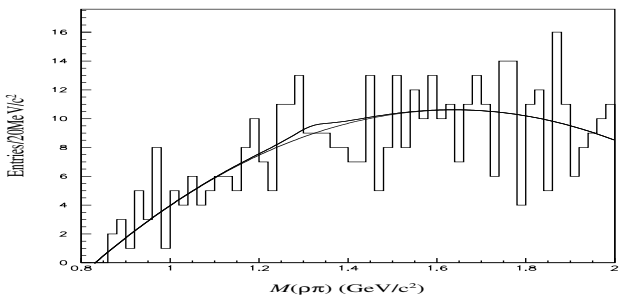

FIG. 3. The $\rho\pi$ invariant mass distribution for events of the type $\psi(2S) \to \rho^0\rho^\mp\pi^\pm$. The curve shows a fit to quadratic background plus an a_2 resonance (see text).

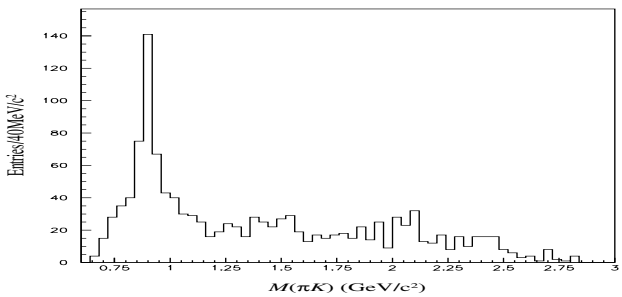

FIG. 4. The $\pi^\pm K^\mp$ invariant mass distribution for $\psi(2S) \to \pi^+\pi^- K^+K^-$ events (4 entries/event).

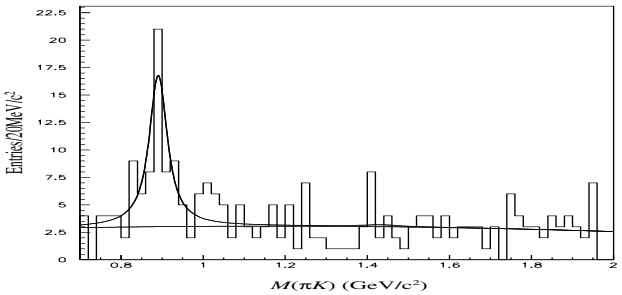

FIG. 5. The invariant mass distribution for $\pi^\pm K^\mp$ tracks recoiling against a K^{*0} for $\psi(2S) \to \pi^+\pi^- K^+K^-$ events. The curve shows a fit to quadratic background plus K^{*0} and K_2^{*0} resonances (see text).

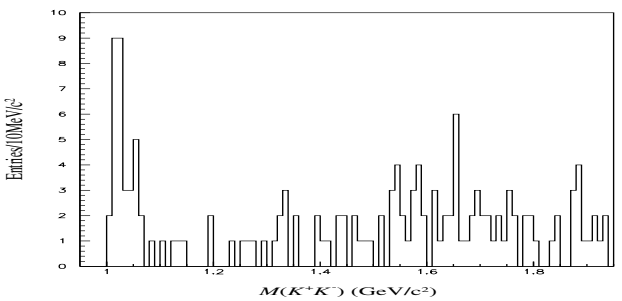

FIG. 6. The K^+K^- invariant mass distribution for $\psi(2S) \to K^+K^-K^+K^-$ events (4 entries/event).

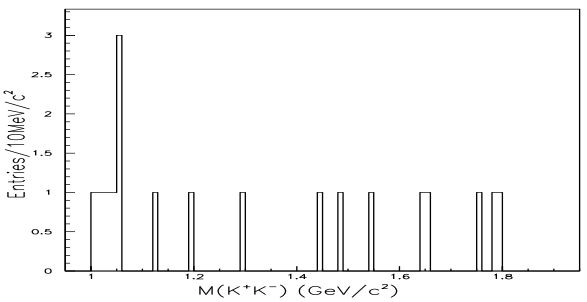

FIG. 7. The invariant mass distribution of K^+K^- pairs recoiling against candidate ϕ mesons for $\psi(2S) \to K^+K^-K^+K^-$ events. Three events fall into 80 MeV/c^2 region around the f_2' mass.