$\psi(2S)$ 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 $\omega f_2$, $\rho a_2$, $K^*\overline{K} + c.c.$, and $\phi f_1(1525)$ that are, in each case, significantly smaller than the corresponding branching fractions for the $J/\psi$ meson, scaled according to the expectations of perturbative QCD.

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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 $J/\psi$ 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 $|\Psi(0)|^2$, 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 $J/\psi$ and $\psi(2S)$ decay branching ratios will scale as $|Q_h|^2 B(J/\psi \to h)\approx |Q_h|^2 B(J/\psi \to e^+e^-)$,

where the leptonic branching fractions are taken from the Particle Data Group (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 $Q_{K^*\overline{K}}$ are given in Table I.
$Q_{K\bar{K}}$ 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 $J/\psi$ 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 $\psi(2S) \to \omega f_2$, $\rho a_2$, $K^0\bar{K}^{*0} + c.c.$, and $\phi f_2^0$ (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 T magnetic field provides tracking and energy-loss ($dE/dx$) information. The momentum resolution is $\sigma_p/p = 1.7% \sqrt{1 + p^2/(\text{GeV}/c)}$, 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 a resolution of about 450 ps for hadrons. Radially outside the TOF are an electromagnetic calorimeter with a resolution of $\sigma_E/E = 0.22/\sqrt{E} \,(\text{GeV})$, $\sigma_\phi = 4.5$ mrad, and $\sigma_\theta = 12$ mrad, and an array of $\mu$ counters that are interspersed inside the steel plates that return the solenoid’s magnetic flux.

For the $\psi(2S) \to \omega f_2$ and $\rho a_2$ decay channels, we use the reaction $\psi(2S) \to \pi^+ \pi^- \pi^+ \pi^- \pi^0$; for the $\psi(2S) \to K^{0}\bar{K}^{*0} + c.c.$ and $\phi f_2^0$ 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 $\pi$ or $K$ tracks with a 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 $2.5\sigma$ ($\sigma = 14$ MeV) of the $\pi^0$ mass are assigned as candidate $\pi^0$s. The detection efficiency is determined using $1 \times 10^4$ or $2 \times 10^4$ Monte Carlo (MC)-simulated events that are generated with a uniform phase space distribution. The $\pi$ or $K$ decays in the detector according to the PDG [2] lifetimes 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 $J/\psi$ 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 $J/\psi$ 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 $\omega$ signal with a mass resolution $\sigma = 13.4$ MeV. Candidate $\omega$ 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 $\omega$ mesons. There is no obvious signal in the region of $f_2(1270)$. A fit to the spectrum using a Breit-Wigner function with mass and width fixed at the PDG values ($m = 1275$ MeV, $\Gamma = 185$ MeV) and convoluted with a Gaussian resolution function with $\sigma = 12.3$ MeV, together with a quadratic background shape, yields $8.8 \pm 9.2$ $\omega f_2$ 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 $\pi^0$ and the experimental efficiency of 0.074, we determine an upper limit on the branching fraction of

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

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 $\psi(2S) \to \rho a_2 \to \rho \pi \pi$. Here we select the $\pi^+ \pi^-$ and $\pi^0 \pi^0$ combination that has the minimum value of the quantity [6]

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

and require this minimum value to be less than 200 MeV. The combined $\rho^0 \pi^0$ and $\rho^+ \pi^-$ invariant mass plot, shown in Fig. 3, has no indication of an $a_2$ 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 ($m = 1318.1$ MeV, $\Gamma = 107$ MeV) and a quadratic background function gives $3.9 \pm 15.7$ $a_2$ events, which correspond to less than 29.6 events at the 90% confidence level. Using isospin

![FIG. 1. The $\pi^+ \pi^- \pi^0$ invariant mass distribution for $\psi(2S) \to \pi^+ \pi^- \pi^+ \pi^- \pi^0$ events (four entries/event).](image-url)
invariance to correct for the unseen $a_2 \to \rho \pi$ decay channels and the MC-determined experimental efficiency of 0.074, we determine
\[
B(\psi(2S) \to \rho a_2) < 2.3 \times 10^{-4} \quad \text{(C.L. = 90%)}. \]

In the selection of $\pi^+ \pi^- K^+ K^-$ final states, each event has four possible $\pi^+, \pi^-, K^+, K^-$ track assignments. For each assignment that satisfies the four-constraint kinematic fit with a probability greater than 0.01, the TOF and $dE/dx$ measurements and the kinematic fit quality are combined to determine a global $\chi^2$. The track assignment with the smallest global $\chi^2$ 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, $\Gamma = 50.5$ MeV) and $K_2^{*0}$ ($m = 1432.4$ MeV, $\Gamma = 109$ 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 $1.4 \pm 0.6 K^{*0} K_2^{*0}$ events, which imply a 90% confidence level upper limit of 17.2 events. Using the isospin ratio $K^{*0}\pi^- : K_2^{*0}\pi^0 = 2:1$ for both the $K^{*0}$ and $K_2^{*0}$ decays and the MC-determined efficiency of 0.171, we determine the limit
\[
B(\psi(2S) \to K^{*0}\overline{K}_2^{*0} + \text{c.c.}) < 1.2 \times 10^{-4} \quad \text{(C.L. = 90%)}. \]

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 $K^+ K^-$

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

FIG. 3. The $\rho \pi$ invariant mass distribution for events of the type $\psi(2S) \to \rho^0 \rho^\mp \pi^\mp$. 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 (four 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).
pairs with $m_{K^+K^-} < 1040$ MeV as candidate $\phi$ mesons. Figure 7 shows the invariant mass distribution for the $K^+K^-$ pairs that are recoiling against candidate $\phi$ 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, $\Gamma = 76$ MeV). The 90% confidence level 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

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

Table I summarizes the results of branching fraction measurements for the $\psi(2S) \rightarrow VT$ decay modes reported here. For comparison, the table includes the data for the corresponding $J/\psi$ decays [7] as well as the ratios of the $\psi(2S)$ to $J/\psi$ branching fractions. All four $\psi(2S) \rightarrow VT$ decay modes are suppressed by a factor of at least 3 compared to the expectations of Eq. (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 $K^*\bar{K}$ 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 $\omega f_2^+, \rho_a^s f_2^+, K^{*0}\bar{K}^{*0}$, 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 $J/\psi$ branching fraction according to expectations based on perturbative QCD. The puzzle of the hadronic decays of the $J/\psi$ and $\psi(2S)$ extends from the $VP$ decay to the $VT$ decays.

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*Deceased.


[7] For the first three decays, we use the PDG [2] recommended values of the $J/\psi$ branching fractions. For $J/\psi$ decay to $\phi f_2^0$, 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 $f_2(1710)$.
