Recent Results of $\psi(2S)$ Decays at BES

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Abstract

Using 14 million $\psi(2S)$ data sample collected with BES at BEPC, $\psi(2S) \rightarrow VT, K_S^0 K^0_L$ (also $J/\psi \rightarrow K_S^0 K^0_L$), and $\chi_{cJ} \rightarrow B\overline{B}$ decays are measured and compared with theoretical model predications.

Charmonium physics is one of the interesting and intriguing field of particle physics. Charmonium provides us an excellent and simple system to study QCD, the production and decay mechanisms of heavy quarkonia and light hadron spectra from its decays, and can be treated non-relativistically. Using 14 M $\psi(2S)$ data sample collected with BEijing Spectrometer (BES) at BEPC, $\psi(2S) \rightarrow VT, K_S^0 K^0_L$ (also $J/\psi \rightarrow K_S^0 K^0_L$), and $\chi_{cJ} \rightarrow B\overline{B}$ decays are measured and compared with theoretical model predications. The BES detector is described in detail in Ref.[1].

1 Study of VT Channel in $\psi(2S)$ Decay

Both $J/\psi$ and $\psi(2S)$ decays are expected to be dominated by annihilation into three gluons, with widths that are proportional to the square of the $c\bar{c}$ wave function at the origin [2]. This yields the pQCD expectation (so-called “12 % ” rule) that

$$Q_h = \frac{B_{\psi(2S) \rightarrow X_h}}{B_{J/\psi \rightarrow X_h}} = \frac{B_{\psi(2S) \rightarrow e^+e^-}}{B_{J/\psi \rightarrow e^+e^-}} = (12.3 \pm 0.7)\%.$$ (1)

The violation of this rule was firstly revealed by MARK-I in VP channel (such as $\rho\pi$ and $K^*\overline{K}$ channel) [3], which leads to famous “$\rho\pi$ puzzle”. This phenomenon was then confirmed by BES at higher sensitivity [4]. Afterwards, BES collaboration presented many other observations, one of them is about VT channel. Based on BES-I 4 M data, the upper-limits of four VT channels, $\omega_2(1270)$, $\rho_2(1320)$, $K^*(892)^0 K_2^0(1430)^0 + c.c.$, and $f_2(1525)^0$, were given [5]. Now with BES-II 14 M $\psi(2S)$ date sample, all these upper-limits have been determined to be branching fractions. For these decay modes, studies focus on four-charged-track final states, such as $K^+ K^- \pi^+ \pi^-$ or $K^+ K^- K^+ K^-$, and those with additional two photons decayed from $\pi^0$, such as $\pi^+ \pi^- \pi^+ \pi^- \gamma \gamma$ or $K^+ K^- \pi^+ \pi^- \gamma \gamma$. After event selection, the invariant mass distributions for different channels are shown in Fig. 4. From the data fitting, the observed numbers of events are obtained, and M.C. simulation gives the corresponding efficiencies. The final results are shown in Table 1 together with statistical and systematic errors, and the resulting errors are at the level of 30 to 40 percent. Combining the corresponding results of $J/\psi$ decay from PDG2002 [6], the $Q_h$ values were calculated as listed in Table 1. Comparing with 12 % rule, it is seen that the $Q_h$ value of VT channel is greatly suppressed.
2 First Observation of $K_S^0 K_L^0$ in $\psi(2S)$ Decay

For pseudoscalar meson pairs (PP) decays, the theoretical motivation, besides the pCQD rule test, involves the phase study which is very important in understanding the strong interaction mechanism of charmonium decay. A recent phenomenological analysis predicts a relation between the branching ratio of $K_S^0 K_L^0$ and the phase between the three-gluon and the one-photon annihilation amplitudes [7]. So the measurement of the $K_S^0 K_L^0$ branching ratio is important to determine the phase. From data analysis point of view, the event topology of $\psi(2S) \rightarrow K_S^0 K_L^0$ is fairly prominent: the neutral $K_L$ almost leaves no information in Main Drift Chamber due to long decay lifetime, while the $K_S$ swiftly decays into two pions. By the virtue of this characteristic topology of event, two good charged tracks are required with net charge zero; in addition, secondary vertex requirement is applied for $K_S$ identification. With these requirements, the distribution of the momentum of $K_S$ is obtained as shown in Fig. 2(a). The different shaded histograms indicate different estimation and simulation of background, whose shape in the
production is estimated according to Monte Carlo simulation for the following decay Σ Λ. The mass spectrum, as Refs. [10] and [11]. A recent analysis involving theoretical papers of interest are given in Ref. [9], and experimental results from BES could refer χ ratios of 3 Study of The large sample of ψ inputs correspond to three groups of branching ratios of three-gluon and the one-photon annihilation amplitudes is shown in Fig. 3(a), where three K. As (28 the momentum distribution of ψ is considerably larger than that of the PDG value: B(ψ → J/ψ to be (1 5). The similar study has also been made for J/ψ → K^0 S K^0 L decay. The momentum distribution of K_S_L is shown in Fig. 2(b) and the branching ratio is worked out to be (1.86 ± 0.47 ± 0.63) x 10^{-4}. It is worth while to notice that the BES measurement result is considerably larger than that of the PDG value: B(J/ψ → K^0 S K^0 L = (1.08 ± 0.47) x 10^{-4}. In contrast with VT channel, the Q_h value for K^0 S K^0 L channel is enhanced greatly. Using BES measured branching ratios of K^0 S K^0 L decay from J/ψ and ψ(2S), the Q_h value is calculated as (28.2 ± 4.7)%. Comparing to 12% rule, the deviation is greater than 3 σ. According to Ref. [7], the relation between branching ratio of ψ(2S) → K^0 S K^0 L and the phase between the three-gluon and the one-photon annihilation amplitudes is shown in Fig. 3(a), where three inputs correspond to three groups of branching ratios of ψ(2S) to π^+π^− or K^+K^−. Using the K^0 S K^0 L branching ratio, the phase is determined to be either −85° or 130°. Here the most interesting result is the large phase which supports the theoretically favored orthogonal phase assumption. S.

### 3 Study of χ_{cJ} Decays

The large sample of ψ(2S) decays permits studies of χ_{cJ} decays with high precision. Some theoretical papers of interest are given in Ref. [9], and experimental results from BES could refer to Refs. [10] and [11]. A recent analysis involving χ_{cJ} decay is the measurement of branching ratios of χ_{cJ} → ΛΛ. The detailed information could be found in Ref. [12], where γπ^+π^−p̅p̅ events with π^+π^−p̅p̅ mass in the χ_{cJ} mass region are studied carefully. The background from non-ΛΛ event is estimated from the Λ mass sidebands of data distribution, while that from channels with ΛΛ production is estimated according to Monte Carlo simulation for the following decay modes: ψ(2S) → ΛΛ, Σ^0 , ΛΣ^0 + c.c., ΛΣ^0 , and ψ(2S) → γχ_{cJ}, χ_{cJ} → Σ^0 → γγΛΛ. In addition, ψ(2S) → π^+π^-J/ψ → π^+π^-p̅p̅ as background is also taken into consideration. The background shape is determined by combining two kinds of background estimation, and the observed numbers of events are obtained from fitting of the selected ΛΛ mass spectrum, as shown in Fig. 3(b), and the branching ratios could be found in Table 1.

| VT channel | B_{ψ(2S)} (10^{-4}) | B_{J/ψ} (10^{-4}) | Q_h (%) |
|------------|------------------|------------------|--------|
|            | (from BES)       | (from PDG2002)   |        |
| ωf_2       | 2.05 ± 0.41 ± 0.46 | 4.3 ± 0.6       | 4.8 ± 1.5 |
| ρ_02       | 2.55 ± 0.73 ± 0.60 | 10.9 ± 2.2     | 2.3 ± 1.1 |
| K^+K^0_L + c.c. | 1.64 ± 0.33 ± 0.41 | 6.7 ± 2.6     | 2.4 ± 1.2 |
| φ_J^0       | 0.48 ± 0.14 ± 0.12 | 1.23 ± 0.06 ± 0.20 | 3.9 ± 1.6 |

PP channel | B_{ψ(2S)} (10^{-4}) | B_{J/ψ} (10^{-4}) | Q_h (%) |
|------------|------------------|------------------|--------|
|            | (from BES)       | (from BES)       |        |
| K^0 S K^0_L | 5.25 ± 0.47 ± 0.63 | 1.86 ± 0.43 ± 1.2 | 28.2 ± 4.7 |

| Decay mode | B_{Exp.} (10^{-4}) | B_{The.} (10^{-4}) | R_{Exp./The.} |
|------------|------------------|------------------|---------------|
|            | (from BES)       | (by COM)        |               |
| χ_{c0} → ΛΛ | 4.7^{+1.4}_{−1.0} | 1.0             |               |
| χ_{c1} → ΛΛ | 2.6^{+1.0}_{−0.9} | 0.366           | 7.1           |
| χ_{c2} → ΛΛ | 3.3^{+1.3}_{−1.3} | 0.333           | 9.9           |

* This value from DM2 only.

Table 1: The results of ψ(2S) and χ_{cJ} decays.

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vicinity of signal region is described by exponential function. For signal events, the Gaussian function is used to fit the observed number of events. The final branching ratio is worked out to be (5.25 ± 0.47 ± 0.63) x 10^{-5}. The similar study has also been made for J/ψ → K^0 S K^0 L decay. The moment
Figure 2: The $K_S^0$ momentum distribution for (a) $\psi(2S)$ decay and (b) $J/\psi$ decay. The dots with error bars are data, the dark shaded histogram is from $K_S^0$ mass sideband events, and the light shaded histogram is Monte Carlo simulated backgrounds. The curves shown in the plot are from a best fit of the distribution.

(a) $\psi(2S)$ Decay
(b) $J/\psi$ Decay

Figure 3: (a) $\psi(2S) \rightarrow K_S^0 K_L^0$ branching ratio as a function of the relative phase for three different inputs: input one based on DASP results; input two on BES results; input three on $K^+ K^-$ result from BES and $\pi^+ \pi^-$ result derived from pion form factor (for detail information, see Ref. [7]). (b) Mass distribution of $\gamma \Lambda \bar{\Lambda}$ candidates, fit with three mass resolution smeared Breit-Wigner functions and a background as estimated from data sideband and Monte Carlo simulation.

(a) Relation between $\mathcal{B}(K_S^0 K_L^0)$ and phase
(b) Mass distribution of $\gamma \Lambda \bar{\Lambda}$
For comparison, the relevant theoretical results are also listed in Table I, where the theoretical calculation is based on Color Octet Mechanism (COM). According to the values listed in the table, it could be seen the results on $\chi_{c1}$ and $\chi_{c2}$ decays only agree marginally with model predictions.

4 Summary

Based on 14 M $\psi(2S)$ data sample, the branching ratios of four VT channels, $\omega f_2, \rho a_2, K^* K^*_2 + \text{c.c.,}$ and $\phi f_2^*$ are measured. The suppression of this decay mode with respect to “12%” rule is confirmed with better precision. The final state $K^0_S K^*_0$ is first observed in $\psi(2S)$ decay. The $Q_h$ of this final state is calculated and is considerably enhanced comparing with “12%” rule. In addition, using the branching ratio of $\psi(2S) \rightarrow K^0_S K^*_0$, the phase between the three-gluon and the one-photon annihilation amplitudes is determined to be either $-85^\circ$ or $130^\circ$. The branching ratios of $\chi_{cJ} \rightarrow \Lambda \Lambda$ are measured, with these results, the effectiveness of the calculation based on Color Octet Mechanism was tested.

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