Recent BES results on charmonium decays

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Recent results on charmonium decays at BES/BEPC are reported, including the observation of $\psi' \rightarrow K^0_S K^0_L$, $\psi \rightarrow \text{Vector Tensor}$ for the measurement of the relative phase between the strong and electromagnetic decays of $\psi'$ and a test of the pQCD "12% rule" between $\psi'$ and $J/\psi$ decays, the study of $\psi' \rightarrow \gamma\gamma J/\psi$ for the determination of $\psi' \rightarrow \pi^0 J/\psi$, $\eta/\psi$, $\gamma_\chi_{c1}$ and $\gamma_\chi_{c2}$ decay branching fractions; the test of the color-octet mechanism via $X_{c1} \rightarrow p\bar{p}$ and $X_{c2} \rightarrow A\bar{A}$; and a search for the CP violating process $\psi' \rightarrow K^0_S K^0_L$.

1 BES experiment and the data samples

The data samples used for the analyses are taken with the Beijing Spectrometer (BESII) detector at the Beijing Electron-Positron Collider (BEPC) storage ring at a center-of-mass energies corresponding to $M_{\psi'}$ and $M_{J/\psi}$. The data samples contain $(14 \pm 0.6) \times 10^6 \psi'$ events and $(57.7 \pm 2.7) \times 10^6 J/\psi$ events, as determined from inclusive hadronic decays.

2 Observation of $\psi' \rightarrow K^0_S K^0_L$

It has been determined that for many two-body exclusive $J/\psi$ decays the relative phases between the three-gluon and the one-photon annihilation amplitudes are near $90^\circ$. For $\psi'$ decays, the available information about the phase is much more limited because there are fewer experimental measurements. The analysis of $\psi' \rightarrow \text{Vector Pseudoscalar (VP)}$ decays shows that the phase could be the same as observed in $J/\psi$ decays, but it could not rule out the possibility that the phase is near $180^\circ$ as suggested in Ref. due to the big uncertainties in the experimental data. A measurement of the relative phase in $\psi' \rightarrow \text{Pseudoscalar Pseudoscalar (PP)}$ is suggested in Ref. by searching for $\psi' \rightarrow K^0_S K^0_L$.

BESII searches for $\psi' \rightarrow K^0_S K^0_L$ by reconstructing the monochroic $K^0_S$ in the 14 M $\psi'$ data sample. The signal, as shown in Fig. 1, is very significant (about 13σ), and the branching
fraction is measured to be \( B(\psi' \rightarrow K_S^0 K_L^0) = (5.24 \pm 0.47 \pm 0.48) \times 10^{-5} \). This branching fraction, together with branching fractions of \( \psi' \rightarrow \pi^+\pi^- \) and \( \psi' \rightarrow K^+K^- \), are used to extract the relative phase between the three-gluon and the one-photon annihilation amplitudes of the \( \psi' \) decays to pseudoscalar meson pairs. It is found that a relative phase of \((-82 \pm 29)^\circ\) or \((+121 \pm 27)^\circ\) can explain the experimental results.

A similar analysis of the \( J/\psi \) data sample yields an improved measurement of the \( J/\psi \rightarrow K_S^0 K_L^0 \) (see Fig. 1) branching fraction: \( B(J/\psi \rightarrow K_S^0 K_L^0) = (1.82 \pm 0.04 \pm 0.13) \times 10^{-4} \), which is more than 4\( \sigma \) larger than the world average. Comparing with the corresponding branching fraction for \( \psi' \rightarrow K_S^0 K_L^0 \), one gets \( Q_{\psi} = \frac{B(\psi' \rightarrow K_S^0 K_L^0)}{B(J/\psi \rightarrow K_S^0 K_L^0)} = (28.8 \pm 3.7)\% \). This result indicates that \( \psi' \) decays is enhanced by more than 4\( \sigma \) relative to the “12% rule” expected from pQCD, while for almost all other channels where the deviations from the “12% rule” are observed, \( \psi' \) decays are suppressed.

The violation of the “12% rule” in \( K_S^0 K_L^0 \) mode is explained in Ref. in the S- and D-wave mixing model of the \( \psi' \) state. In this scenario, the \( \psi(3770) \), also an S- and D-wave mixed charmonium state will have a decay branching fraction to \( K_L^0 K_L^0 \) between \((0.12 \pm 0.07) \times 10^{-5}\) and \((3.8 \pm 1.1) \times 10^{-5}\). This need to be tested with the large \( \psi(3770) \) data samples at CLEOc and BESIII.

3 Observation of \( \psi' \rightarrow \text{Vector Tensor} \)

Four Vector Tensor (VT) decay channels \( \psi' \rightarrow \omega f_2(1270) \rightarrow \pi^+\pi^-\pi^0, \rho_2(1320) \rightarrow \pi^+\pi^-\pi^0, K^*(892)^0 K^*(1430)^0 + c.c., \phi f_2(1525) \rightarrow K^+K^-K^+K^- \) are investigated to test the pQCD “12% rule”. Previous BESI results on these channels reveal that these VT decay modes are suppressed compared to the perturbative QCD prediction. However, the measurements, using about \( 4 \times 10^6 \) \( \psi' \) events, determined only upper limits or branching fractions with large errors. These analyses are updated with \( 14 \times 10^6 \) \( \psi' \) events, and signals of all these four channels are observed. The statistical significance for all four channels are larger than 3\( \sigma \); those for \( \omega f_2(1270) \) and \( K^*(892)^0 K^*(1430)^0 + c.c. \) are larger than 5\( \sigma \). Table 1 summarizes the results of the four branching fraction measurements, as well as the corresponding branching fractions of \( J/\psi \) decays, and the ratios of the \( \psi' \) to \( J/\psi \) branching fractions. All four VT decay modes are suppressed by a factor of 3 to 5 compared with the pQCD expectation.

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Table 1: Branching fractions measured for $\psi' \rightarrow Vector\ Tensor$. Results for corresponding $J/\psi$ branching fractions are also given as well as the ratio $Q_x = \frac{B(\psi' \rightarrow X)}{B(J/\psi \rightarrow X)}$.

| $X$     | $N_{obs}$ | $\epsilon(\%)$ | $B(\psi' \rightarrow X) \times 10^{-4}$ | $B(J/\psi \rightarrow X) \times 10^{-4}$ | $Q_x(\%)$ |
|---------|-----------|-----------------|----------------------------------------|----------------------------------------|-----------|
| $\omega_2$ | 62 ± 12   | 4.25 ± 0.10     | 2.05 ± 0.41 ± 0.38                     | 4.3 ± 0.6                              | 4.8 ± 1.5 |
| $\rho_0$  | 112 ± 31  | 6.42 ± 0.06     | 2.55 ± 0.73 ± 0.47                     | 10.9 ± 2.2                             | 2.3 ± 1.1  |
| $K^*T_2$  | 93 ± 16   | 16.2 ± 0.2      | 1.86 ± 0.32 ± 0.43                     | 6.7 ± 2.6                              | 2.8 ± 1.3  |
| $d'f_2$  | 19.7 ± 5.6 | 14.8 ± 0.2      | 0.44 ± 0.12 ± 0.11                     | 1.23 ± 0.21                            | 3.6 ± 1.5  |

4 Analysis of $\psi' \rightarrow \gamma\gamma J/\psi$

$\psi' \rightarrow \pi^0 J/\psi$, $\eta J/\psi$ and $\gamma_{\chi_c1,2}$ decay branching ratios are determined by measuring $\gamma\gamma J/\psi$ $J/\psi \rightarrow e^+e^-$ or $\mu^+\mu^-$ final states. The results are shown in Table 2.

| Channel | $\gamma\gamma J/\psi$ | $\eta J/\psi$ |
|---------|------------------------|---------------|
| Final state | $\gamma e^+ e^-$ | $\gamma \mu^+ \mu^-$ | $\gamma e^+ e^-$ | $\gamma \mu^+ \mu^-$ |
| $\BR(\%)$ | 0.139 ± 0.020 ± 0.012 | 0.147 ± 0.019 ± 0.013 | 2.91 ± 0.12 ± 0.21 | 3.06 ± 0.14 ± 0.25 |
| Combine BR (\%) | 1.91 ± 0.14 ± 0.23 | 2.03 ± 0.15 ± 0.25 |

The BES $B(\psi' \rightarrow \pi^0 J/\psi)$ measurement has improved precision by more than a factor of two compared with other experiments, and the BES $\psi' \rightarrow \eta J/\psi$ branching fraction is the most accurate single measurement. The $B(\psi' \rightarrow \pi^0 J/\psi)$ agrees better with the Mark-II result than with the Crystal Ball result, while $B(\psi' \rightarrow \gamma_{\chi_c1,2})$ agrees well with the Crystal Ball results. The measurements are used to test various models in calculating the $\psi'$ decays rates.

5 Test of COM in P-wave charmonium Baryonic decays

Hadronic decay rates of P-wave quarkonium states provide good tests of QCD. The decays $\chi_{cJ} \rightarrow p\bar{p}$ have been calculated using different models, and recently, the decay branching fractions of $\chi_{cJ} \rightarrow baryon$ and anti-baryon pairs were calculated including the contribution of the color-octet fock states. Using the $\chi_{cJ} \rightarrow p\bar{p}$ branching fractions as input to determine the matrix element, the partial widths of $\chi_{cJ} \rightarrow \Lambda\Lambda$ are predicted to be about half of those of $\chi_{cJ} \rightarrow p\bar{p}$, for $J = 1$ and 2. As shown in Table 3, the measurements of $\chi_{cJ} \rightarrow \Lambda\Lambda$ together with the branching fractions of $\chi_{cJ} \rightarrow p\bar{p}$ from the same data sample, indicate that $\chi_{cJ} \rightarrow \Lambda\Lambda$ is enhanced relative to $\chi_{cJ} \rightarrow p\bar{p}$, as compared with the color-octet mechanism calculation.

Table 3: Branching fractions of $\chi_{cJ} \rightarrow \Lambda\Lambda$ and $\chi_{cJ} \rightarrow p\bar{p}$, and $R_\Lambda = \frac{B(\chi_{cJ} \rightarrow \Lambda\Lambda)}{B(\chi_{cJ} \rightarrow p\bar{p})}$.

| Final state | $\chicj \rightarrow \Lambda\Lambda (10^{-5})$ | $\chi_{cJ} \rightarrow p\bar{p} (10^{-5})$ | $R_\Lambda$ |
|-------------|---------------------------------------------|---------------------------------------------|-------------|
| $\chicj \rightarrow \Lambda\Lambda$ | $47^{+14}_{-12} \pm 10$ | $26^{+14}_{-6} \pm 6$ | $33^{+13}_{-12} \pm 7$ |
| $\chicj \rightarrow p\bar{p}$       | $27.1^{+4.3}_{-3.5} \pm 4.7$ | $5.7^{+1.5}_{-1.4} \pm 0.9$ | $6.5^{+2.1}_{-2.0} \pm 1.0$ |
| $R_\Lambda$ | $1.73 \pm 0.63$ | $4.6 \pm 2.3$ | $5.1 \pm 3.1$ |
Search for $\psi'$ and $J/\psi \rightarrow K_S^0K_S^0$

The CP violating processes $J/\psi \rightarrow K_S^0K_S^0$ and $\psi' \rightarrow K_S^0K_S^0$ are searched for using the $J/\psi$ and $\psi'$ samples. One candidate in each case is observed, in agreement with the expected background level. The upper limits on the branching ratios are determined to be $\mathcal{B}(J/\psi \rightarrow K_S^0K_S^0) < 1.0 \times 10^{-6}$ and $\mathcal{B}(\psi' \rightarrow K_S^0K_S^0) < 4.6 \times 10^{-6}$ at the 95% C.L. The former is much more stringent than the previous Mark-III measurement, and the latter is the first search for this channel in $\psi'$ decays. The current bounds on the production rates are still far beyond the sensitivity needed for testing the EPR paradox, and even farther for CP violation.

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