Hadronic Decays of Charmonia from BESII

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Recent results on charmonia decays at BESII/BEPC are reported, including the observation of $\psi' \rightarrow K^0_S K^0_L$, $\psi' \rightarrow Vector Tensor$ and $\psi' \rightarrow Vector Pseudoscalar$ 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 test of the color-octet mechanism via $\chi_{cJ} \rightarrow p p$ and $\chi_{cJ} \rightarrow \Lambda \bar{\Lambda}$; the first observation of $\chi_{c0} \rightarrow f_0(980) f_0(980)$; and a study of the $\psi'$ and $\chi_{cJ}$ decays with $K^0_S K^0_L$ in the final states.

Keywords: Charmonium; hadronic decays; pQCD.

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 $\psi' \rightarrow Vector Pseudoscalar$ (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 $\psi' \rightarrow Pseudoscalar Pseudoscalar$ (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. is very significant (about $13\sigma$), and the branching fraction is measured to be $B(\psi' \rightarrow K^0_S K^0_L) = (5.24 \pm 0.47 \pm 0.48) \times 10^{-5}$. 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 \((-82 \pm 29)\)° or \((+121 \pm 27)\)° can explain the experimental results.

A similar analysis of the \( J/\psi \) data sample yields an improved measurement of the \( J/\psi \rightarrow K_0^0 K_0^0 \) (see Fig. 1) branching fraction \( B(J/\psi \rightarrow K_0^0 K_0^0) = (1.82 \pm 0.04 \pm 0.13) \times 10^{-4} \), which is more than 4\( \sigma \) larger than the world average. Comparing with the corresponding branching fraction for \( \psi' \rightarrow K_0^0 K_L^0 \), one gets \( Q_h = \frac{B(\psi' \rightarrow K_0^0 K_L^0)}{B(J/\psi \rightarrow K_0^0 K_L^0)} = (28.8 \pm 3.7)\% \). This result indicates that \( \psi' \) decays is enhanced by more than 4\( \sigma \) relative to the “12% rule” expected from perturbative QCD (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 \( K_0^0 K_L^0 \) mode is explained in Ref. 11 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 \( K_0^0 K_L^0 \) 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 \( \psi' \rightarrow \omega f_2(1270) \rightarrow \pi^+\pi^-\pi^+\pi^-\pi^0 \)
\( \rho a_2(1320) \rightarrow \pi^+\pi^-\pi^+\pi^-\pi^0 \)
\( K^*(892)0 K_2^*(1430)0 + c.c. \rightarrow \pi^+\pi^- K^+K^- \)
and \( \phi f_2'(1525) \rightarrow K^+K^-K^+K^- \) are investigated to test the pQCD “12% rule”.

Previous BESI results reveal that these VT decay modes
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Table 1. Branching fractions measured for $\psi' \to Vector\ Tensor$. Results for corresponding $J/\psi$ branching fractions are also given as well as the ratio $Q_X = \frac{B(\psi' \to X)}{B(J/\psi \to X)}$.

| X            | $N^{obs}$ | $B(\psi' \to X)(\times 10^{-4})$ | $B(J/\psi \to X)(\times 10^{-3})$ | $Q_X(\%)$ |
|--------------|-----------|---------------------------------|----------------------------------|-----------|
| $\omega f_2$ | 62 ± 12   | 2.05 ± 0.41 ± 0.38              | 4.3 ± 0.6                        | 4.8 ± 1.5 |
| $\rho a_2$   | 112 ± 31  | 2.55 ± 0.73 ± 0.47              | 10.9 ± 2.2                       | 2.3 ± 1.1 |
| $K^{*0}K_2^0 + c.c.$ | 93 ± 16 | 1.86 ± 0.32 ± 0.43 | 6.7 ± 2.6 | 2.8 ± 1.3 |
| $\phi f_2'$  | 19.7 ± 5.6 | 0.44 ± 0.12 ± 0.11             | 1.23 ± 0.21                      | 3.6 ± 1.5 |

are suppressed compared to the pQCD 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 $K^*(892)^0K$ (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.

4. Observation of $\psi' \to Vector\ Pseudoscalar$ (preliminary)

This mode is also investigated to test the pQCD “12% rule” and to study the relative phase between strong and electromagnetic decays of the charmonium. Here $K^{*+}K^- + c.c.$ and $K^{*0}K^0 + c.c.$ are studied with $K^{*0}_S K^+\pi^- + c.c.$ final state.

In the event, $K^{*0}_S$ is identified through the decay $K^{*0}_S \to \pi^+\pi^-$. Any two oppositely charged tracks are assumed to be pions and their intersection is found with the code used in Ref. 4 a $K^{*0}_S$ candidate should have $\pi^+\pi^-$ invariant mass agree with $K^{*0}_S$ nominal mass and the decay length in the transverse plane ($L_{xy}$) should be large. The four charged tracks are kinematically fitted to further improve the resolution and remove more background.

After above selection, the Dalitz plot of the candidate events is shown in Fig. 2(a). Monte Carlo simulation of $\psi' \to K^*\bar{K} + c.c.$ indicates that $K^{*0}K^0 + c.c.$ appears as a horizontal band and $K^{*+}K^- + c.c.$ as a vertical band. Figure 2(b) shows the invariant mass of $K^{\pm}\pi^\mp$ with an additional cut $m_{K^{\pm}\pi^\mp} > 1.0$ GeV to remove the influence from $K^{*+}K^- + c.c.$, and Figure 2(c) shows the invariant mass of $K^{0}\pi^\pm$ for $K^{*0}_S K^{\pm}\pi^\mp$ candidate events with an additional cut $m_{K^{\pm}\pi^\mp} > 1.0$ GeV to remove the influence from $K^{*0}K^0 + c.c.$ Clear $K^{*+}K^- + c.c.$ and $K^{*0}K^0 + c.c.$ signals are observed in the plots.

The fit of the invariant mass spectra for $K^{\pm}\pi^\mp$ and $K^{0}\pi^\pm$, as shown in Fig. 2(b) and (c), yield $65.6 \pm 3.9 \ K^{*0}K^0 + c.c.$ and $9.6 \pm 4.2 \ K^{*+}K^- + c.c.$ events. Their detection efficiencies are $(9.68 \pm 0.07)\%$ and $(7.25 \pm 0.07)\%$ from Monte Carlo simulation, and their statistical significance are $11\sigma$ and $3.5\sigma$, respectively. The branching fractions are listed in Table 2 compared with the corresponding branching fractions of $J/\psi$ decays, $\psi'$ decays are suppressed relative to the 12% rule expectation.
Fig. 2. Dalitz plot (a) and invariant mass of $K^\pm\pi^\mp$ (b) and of $K^0\pi^\pm$ candidate events after cuts described in the text. The blank dot stands for real data, and the shadow for Monte Carlo simulation of $\psi' \to \psi K^* + c.c.$ (the horizontal cluster for $K^0\bar{K}^0 + c.c.$ and the vertical cluster for $K^{*+}K^- + c.c.$). The curve shows the best fit described in the text.

Table 2. Branching fractions measured for $\psi' \to K^*\bar{K} + c.c.$ (preliminary). Results for corresponding $J/\psi$ branching fractions by PDG are also given as well as the ratios $Q_h = \frac{B(\psi')}{B(J/\psi)}$.

| Channels       | $B(\psi') \times 10^{-5}$ | $B(J/\psi) \times 10^{-4}$ | $Q_h$ (%) |
|----------------|---------------------------|----------------------------|-----------|
| $K^{*+}K^- + c.c.$ | $2.9 \pm 1.4 \pm 0.4$    | $50 \pm 4$                 | $0.58 \pm 0.29$ |
| $K^{*0}\bar{K}^0 + c.c.$ | $15.0 \pm 2.1 \pm 1.7$  | $42 \pm 4$                 | $3.6 \pm 0.7$  |

The ratio $\frac{B(K^{*0}\bar{K}^0 + c.c.)}{B(K^{*+}K^- + c.c.)} = 5.1 \pm 2.5$ shows a large isospin violation between the charged mode and neutral mode of $\psi' \to K^*\bar{K} + c.c.$ decays, this is understandable since the electromagnetic decay amplitudes are different in these two channels.

Contributions from the continuum $e^+e^- \to \gamma^* \to$ hadrons [14][15] are estimated using a data sample of $(6.42 \pm 0.24) \text{ pb}^{-1}$ taken at $\sqrt{s} = 3.65$ GeV, about one-third of the integrated luminosity at the $\psi'$. $2.5 \pm 1.9$ events are observed in $K^*(892)^0\bar{K}^0 + c.c.$, while no events in charged channel. Since the signals are not significant due to the limited statistics, they are not considered in the branching ratio determination above. However, if one assumes the continuum amplitude is indeed at the measured level, the branching fractions of $\psi' \to K^{*+}K^- + c.c.$ and $K^{*0}\bar{K}^0 + c.c.$ can be recalculated by the model proposed in Ref. [2], where the contributions of the continuum and the interference are taken into consideration. The branching fractions are changed to: $B(\psi' \to K^{*+}K^- + c.c.) = 3.1 \times 10^{-4}$ and $B(\psi' \to K^{*0}\bar{K}^0 + c.c.) = 12.7 \times 10^{-4}$, where the uncertainties due to the model are not included.
In conclusion, we present the branching fractions for $\psi' \rightarrow K^{*0}\overline{K}^0 + c.c.$ and $K^{*+}K^- + c.c.$ for the first time, they are suppressed with respect to the pQCD expectation, and a large isospin violation in the charged and neutral mode is observed. This may shed light on the understanding the $\psi'$ decay dynamics.

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 $\chi_{cJ} \rightarrow p\overline{p}$ have been calculated using different models \cite{15}, and recently, the decay branching fractions of $\chi_{cJ} \rightarrow \text{baryon and anti-baryon pairs}$ were calculated including the contribution of the color-octet fock states \cite{16}. Using the $\chi_{cJ} \rightarrow p\overline{p}$ branching fractions as input to determine the matrix element, the partial widths of $\chi_{cJ} \rightarrow \Lambda\overline{\Lambda}$ are predicted to be about half of those of $\chi_{cJ} \rightarrow p\overline{p}$, for $J = 1$ and 2. As shown in Table 3, the measurements of $\chi_{cJ} \rightarrow \Lambda\overline{\Lambda}$ \cite{17} together with the branching fractions of $\chi_{cJ} \rightarrow p\overline{p}$ \cite{18} from the same data sample, indicate that $\chi_{cJ} \rightarrow \Lambda\overline{\Lambda}$ is enhanced relative to $\chi_{cJ} \rightarrow p\overline{p}$, as compared with the color-octet mechanism (COM) calculation \cite{16}.

| $\mathcal{B}(\chi_{cJ} \rightarrow \Lambda\overline{\Lambda}) (10^{-5})$ | $47^{+15}_{-10} \pm 10$ | $26^{+10}_{-6} \pm 6$ | $33^{+15}_{-13} \pm 7$ |
| $\mathcal{B}(\chi_{cJ} \rightarrow p\overline{p}) (10^{-5})$ | $27.1^{+3}_{-3.9} \pm 4.7$ | $5.7^{+1.7}_{-1.5} \pm 0.9$ | $6.5^{+2.4}_{-2.1} \pm 1.0$ |
| $R_B = \mathcal{B}(\chi_{cJ} \rightarrow \Lambda\overline{\Lambda})/\mathcal{B}(\chi_{cJ} \rightarrow p\overline{p})$ | $1.73 \pm 0.63$ | $4.6 \pm 2.3$ | $5.1 \pm 3.1$ |

6. Evidence for $\chi_{c0} \rightarrow f_0(980)f_0(980)$

After thirty years of controversy, the nature of the $f_0(980)$ is still not settled \cite{19,20}, and more experimental results are needed to clarify it. Here we report on the analysis of $\pi^+\pi^-\pi^+\pi^-$ final states from $\chi_{c0}$ decays using the $\psi'$ data sample. Evidence for $f_0(980)f_0(980)$ production from $\chi_{c0}$ decays is obtained for the first time \cite{20}.

The left plot of Figure 3 shows scatter plot of $\pi^+\pi^-$ versus $\pi^+\pi^-$ invariant mass for the events in $\chi_{c0}$ mass region (from 3.30 to 3.48 GeV), and the definition of the signal and background control regions. The signal region is shown in the figure as a circle centered at (0.960, 0.960) GeV and with a radius of 80 MeV, and the background is estimated from the events between two circles with radii of 120 MeV and 160 MeV. There are 65 and 51 events in the signal and background regions, respectively. So the number of $f_0(980)f_0(980)$ events is estimated to be 65 - 51/1.75 = 35.9 \pm 9.0, where 1.75 is the normalization factor – the ratio of the area of background region to that of the signal region. We obtain the signal significance of the $f_0(980)f_0(980)$ of 4.6$\sigma$ using the method described in Ref. \cite{21}. After requiring that the mass of one of the $\pi^+\pi^-$ pairs lies between 0.88 and 1.04 GeV, the mass distribution of the other $\pi^+\pi^-$ pair is shown in the right plot of Fig. 3 (two entries.
per event); there is a strong \( f_0(980) \) signal, and its line shape is similar to other experiments\(^9\).

![Fig. 3. Left: scatter plot of \( \pi^+ \pi^- \) versus \( \pi^+ \pi^- \) invariant mass in the \( f_0(980) \) region for \( \chi_{c0} \) candidate events, the circles show the definition of signal and background regions. Right: \( \pi^+ \pi^- \) mass distribution recoiling against the \( f_0(980) \) (0.88 GeV < \( m_{\pi^+\pi^-} < 1.04 \) GeV) for events in the \( \chi_{c0} \) mass region (two entries per event), where the dashed line histogram indicates a rough estimation of background determined from sidebands.](image)

The resulting branching ratio is

\[
B(\psi' \rightarrow \gamma \chi_{c0} \rightarrow \gamma f_0(980)f_0(980) \rightarrow \gamma \pi^+ \pi^- \pi^+ \pi^-) = (6.5 \pm 1.6 \pm 1.3) \times 10^{-5},
\]

and using the PDG\(^9\) average value and error for \( B(\psi' \rightarrow \gamma \chi_{c0}) \), we obtain

\[
B(\chi_{c0} \rightarrow f_0(980)f_0(980) \rightarrow \pi^+ \pi^- \pi^+ \pi^-) = (7.6 \pm 1.9 \text{ (stat)} \pm 1.6 \text{ (syst)}) \times 10^{-4}.
\]

This may help in understanding the nature of \( f_0(980) \).

7. Search for \( \psi' \) and \( J/\psi \rightarrow K_S^0 K_S^0 \)

The CP violating processes \( J/\psi \rightarrow K_S^0 K_S^0 \) and \( \psi' \rightarrow K_S^0 K_S^0 \) are searched for using the \( J/\psi \) and \( \psi' \) samples\(^{22}\). 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 \( B(J/\psi \rightarrow K_S^0 K_S^0) < 1.0 \times 10^{-6} \) and \( B(\psi' \rightarrow K_S^0 K_S^0) < 4.6 \times 10^{-6} \) at the 95\% C. L. The former is much more stringent than the previous Mark-III measurement\(^{23}\) 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\(^{24}\) and even farther for CP violation\(^{25}\).

8. \( \psi' \) and \( \chi_{cJ} \) decays with \( K_S^0 K_S^0 \) in the final states (preliminary)

Since the observed total branching fractions of \( \psi' \) and \( \chi_{cJ} \) (\( J = 0, 1, 2 \)) decays into light hadrons are still small (about 1.5 ~ 11\%)\(^9\). The final states with two \( K_S^0 \) are...
searched for using the $\psi'\rightarrow \pi^+\pi^-K_S^0K_S^0$, $\chi_{cJ}\rightarrow K_S^0K_S^0$, $\pi^+\pi^-K_S^0K_S^0$ and $K^+K^-K_S^0K_S^0$, except for $\chi_{cJ}\rightarrow K_S^0K_S^0$ which has been measured by BES experiment [20], other channels were not observed before.

Figure 4 shows the invariant mass of $K_S^0K_S^0$ in $\gamma K_S^0K_S^0$ channel, and that of $\pi^+\pi^-K_S^0K_S^0$ in $\gamma \pi^+\pi^-K_S^0K_S^0$ channel. Clear $\chi_{cJ}$ states can be seen. Final results of branching fractions are summarized in Table 4. The branching fractions of $\chi_{c0}$ and $\chi_{c2}$ decays to $K_S^0K_S^0$ are measured with improved precision.

![Fig. 4. Invariant mass of $K_S^0K_S^0$ in $\psi'\rightarrow \gamma K_S^0K_S^0$ (top) and invariant mass of $\pi^+\pi^-K_S^0K_S^0$ in $\psi'\rightarrow \gamma \pi^+\pi^-K_S^0K_S^0$ (bottom). The error bars are data and the shaded histograms are background estimated from the $K_S^0$ mass sidebands. The solid lines are the best fit to the data.](image)

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Table 4. Summary of the branching ratio results (preliminary). The first and second errors for branching fractions are statistical and systematic respectively.

| Channel                | n$^{obs}$ | Branching Ratio               |
|------------------------|-----------|--------------------------------|
| $\chi_{c0} \rightarrow K^0_SK^0_S$ | 302 ± 18  | $(3.37 ± 0.20 ± 0.44) \times 10^{-3}$ |
| $\chi_{c1} \rightarrow K^+K^-K^0_SK^0_S$ | 0         | $<2.55 \times 10^{-5}$ (CL=90%) |
| $\chi_{c2} \rightarrow K^+K^-K^0_SK^0_S$ | 64.8 ± 8.0| $(8.9 \pm 1.1 \pm 1.2) \times 10^{-4}$ |
| $\chi_{c0} \rightarrow \pi^+\pi^-K^0_SK^0_S$ | 157 ± 12  | $(6.6 \pm 0.5 \pm 1.1) \times 10^{-3}$ |
| $\chi_{c1} \rightarrow \pi^+\pi^-K^0_SK^0_S$ | 20.4 ± 6.9| $(8.0 \pm 3.1 \pm 1.3) \times 10^{-4}$ |
| $\chi_{c2} \rightarrow \pi^+\pi^-K^0_SK^0_S$ | 62.2 ± 9.2| $(3.24 \pm 0.57 \pm 0.55) \times 10^{-3}$ |
| $\chi_{c0} \rightarrow K^+K^-K^0_SK^0_S$ | 19.2 ± 3.7| $(1.87 \pm 0.36 \pm 0.34) \times 10^{-3}$ |
| $\chi_{c1} \rightarrow K^+K^-K^0_SK^0_S$ | 3.9 ± 2.4 | $(3.1 \pm 1.9 \pm 0.6) \times 10^{-4}$ |
| $\chi_{c2} \rightarrow K^+K^-K^0_SK^0_S$ | 3.0 ± 2.1 | $(3.3 \pm 2.3 \pm 0.6) \times 10^{-4}$ |
| $\psi' \rightarrow \pi^+\pi^-K^0_SK^0_S$ | 83.2 ± 4.4| $(2.20 \pm 0.12 \pm 0.33) \times 10^{-4}$ |

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