Recent results on $\psi(2S)$ decays, including 10 Vector + Pseudoscalar (VP) modes and $p\bar{p}\pi^0(\eta)$, are reported with $14 \times 10^6 \psi(2S)$ events collected with the BESII detector. Cross sections and form factors for $e^+e^- \rightarrow \omega\pi^0$, $\rho\eta$, and $\rho'\eta'$ at the center of mass energies of 3.650, 3.686, and 3.773 GeV are measured simultaneously.

1 Introduction

A strong violation to the “12% rule” predicted by perturbative QCD was first observed by the MarkII experiment in the Vector-Pseudoscalar (VP) meson final states, $\rho\eta$ and $K^{*+}(892)K^-$ c.c. Significant suppressions observed in four Vector-Tensor decay modes make the puzzle even more mysterious. Numerous theoretical explanations have been suggested, but the puzzle still remains one of the most intriguing questions in charmonium physics.

The study on $\psi(2S) \rightarrow p\bar{p}\pi^0(\eta)$ provides a chance to study the $N^*$ resonances, which play important roles on our understanding of the nonperturbative QCD.

2 Analysis of $\psi(2S) \rightarrow \pi^+\pi^-\pi^0$

The selected $\pi^+\pi^-\pi^0$ events are fitted in the helicity amplitude formalism with an unbinned maximum likelihood method using MINUIT. The fit shown in Fig. describes the data reasonably well, and the $\rho(2150)$ serves as an effective description of the high mass enhancement near 2.15 GeV/$c^2$ in $\pi\pi$ mass. The branching fractions of $\psi(2S) \rightarrow \pi^+\pi^-\pi^0$, $\rho(770)\pi$ and $\rho(2150)\pi \rightarrow \pi^+\pi^-\pi^0$ are $(18.1 \pm 1.8 \pm 1.9) \times 10^{-5}$, $(5.1 \pm 0.7 \pm 1.1) \times 10^{-5}$ and $(19.4 \pm 2.5_{-3.4}^{+11.5}) \times 10^{-5}$, respectively, where the first error is statistical and the second one is systematic.
3 Analysis of Electromagnetic Decays $\psi(2S) \rightarrow \omega \pi, \rho \eta$ and $\rho \eta'$

For this analysis, besides the $\psi(2S)$ data sample, we also analyze 6.42 pb$^{-1}$ of continuum data at $\sqrt{s} = 3.650$ GeV, and 17.3 pb$^{-1}$ at the $\psi(3770)$ Table I lists the cross sections of $e^+e^- \rightarrow \omega \pi, \rho \eta$ and $\rho \eta'$ and the corresponding form factors; the branching fractions of $\psi(2S) \rightarrow \omega \pi, \rho \eta$ and $\rho \eta'$ are listed in Table II.

Table 1: Cross sections and form factors measured for $e^+e^- \rightarrow \omega \pi^0, \rho \eta, \rho \eta'$ at $\sqrt{s} = 3.650, 3.686, \text{and} 3.773$ GeV.

| Channel | Samples | $\mathcal{L}$ (pb$^{-1}$) | $N_{\text{obs}}^{\text{cont}}$ | $\epsilon$ (%) | $1 + \delta$ | $\sigma_0$ (pb) | $|F_{VP}|$ (GeV$^{-1}$) |
|---------|---------|----------------|----------------|----------------|-----------|----------------|----------------|
| $\omega \pi^0$ | 3.650 GeV | 6.42 | $7.3^{+3.4}_{-2.7}$ | 5.09 | 1.032 | $24.3^{+11.9}_{-9.0} \pm 4.3$ | 0.051$^{+0.12}_{-0.19}$ |
| | 3.686 GeV | 19.72 | $17.3^{+5.7}_{-5.1}$ | 4.98 | 1.031 | $19.2^{+6.3}_{-5.7} \pm 4.9$ | 0.045$^{+0.08}_{-0.07}$ |
| | 3.773 GeV | 17.3 | $8.6^{+4.0}_{-3.3}$ | 5.09 | 1.028 | $10.7^{+5.0}_{-4.1} \pm 1.7$ | 0.034$^{+0.08}_{-0.07}$ |
| $\rho \eta$ | 3.650 GeV | 6.42 | $2.3^{+1.0}_{-1.4}$ | 10.9 | 1.028 | $8.1^{+4.5}_{-4.9} \pm 1.1$ | 0.030$^{+0.011}_{-0.009}$ |
| | 3.686 GeV | 19.72 | $16.0^{+5.0}_{-5.6}$ | 10.9 | 1.028 | $18.4^{+7.8}_{-8.5} \pm 1.9$ | 0.046$^{+0.011}_{-0.009}$ |
| | 3.773 GeV | 17.3 | $5.8^{+5.3}_{-2.6}$ | 10.7 | 1.026 | $7.8^{+4.3}_{-3.5} \pm 0.8$ | 0.030$^{+0.007}_{-0.006}$ |
| $\rho \eta'$ | 3.650 GeV | 6.42 | $< 4.4$ | 4.33 | 1.021 | $< 89$ | $< 0.192$ |
| | 3.686 GeV | 19.72 | $2.9^{+2.4}_{-1.6}$ | 4.43 | 1.020 | $18.6^{+15.4}_{-10.3} \pm 3.6$ | 0.050$^{+0.021}_{-0.015}$ |
| | 3.773 GeV | 17.3 | $< 3.9$ | 4.56 | 1.019 | $< 28$ | $< 0.106$ |

Fig. 2 shows the results of the form factor $|F_{\omega \pi^0}|$ from our measurements, CMD-2, and DM2, and the calculated value of $|F_{\omega \pi^0}|$ at $s = m^2/\psi$. Curve (A) is predicted by J.-M. Gérard and G. López Castro as:

$$|F_{\omega \pi^0}(s \rightarrow \infty)| = \frac{f_\omega f_\pi}{3\sqrt{2}s},$$

(1)

with $f_\omega = 17.05 \pm 0.28$ and $f_\pi = 0.1307$ GeV, the decay constants of $\omega$ and $\pi$, respectively.
Curve (B) is predicted by Victor Chernyak\cite{12}.

\[ |F_{\omega\pi^0}(s)| = |F_{\omega\pi^0}(0)| \frac{m_\rho^2 M_\rho^2}{(m_\rho^2 - s)(M_\rho^2 - s)}, \]  

(2)

where \( m_\rho \) and \( M_\rho \) are the masses of \( \rho(770) \) and \( \rho(1450) \), respectively. From Fig. 2 our results agree with the description of Eq. 1.

Figure 2: Energy dependence of the \( e^+e^- \rightarrow \gamma^* \rightarrow \omega\pi^0 \) form factor. Curve (A) is calculated with Eq. 1, while curve (B) is calculated with Eq. 2.

4 Measurements of \( \psi(2S) \) decays into \( K^*(892)\bar{K} + c.c. \), \( \phi\pi^0 \), \( \phi\eta \), \( \phi\eta' \), \( \omega\eta \), and \( \omega\eta' \)

For \( \psi(2S) \rightarrow K^*(892)\bar{K} + c.c. \), we study its final state \( K^0 K^{\pm} \rightarrow \pi^+ \pi^- K^{\mp} \)\cite{13}. The other decay modes are studied with \( \phi \) decays to \( K^+K^- \), \( \omega \) to \( \pi^+\pi^-\pi^0 \), \( \eta' \) to \( \eta\pi^+\pi^- \) or \( \gamma\pi^+\pi^- \), and \( \pi^0 \) and \( \eta \) to \( 2\gamma \)\cite{13}. The results are listed in Table 2.

Table 2: Branching fractions and upper limits (90% C.L.) measured for \( \psi(2S) \) decays. Results for corresponding \( J/\psi \) branching fractions and the ratios \( Q_h = \frac{B(\psi(2S) \rightarrow h)}{B(J/\psi \rightarrow h)} \) are also given.

| \( h \)          | \( B(\psi(2S) \rightarrow h) \times 10^{-5} \) | \( B(J/\psi \rightarrow h) \times 10^{-4} \) | \( Q_h \) (%) |
|-------------------|---------------------------------|---------------------------------|----------------|
| \( \rho\pi \)     | 5.1 \pm 0.7 \pm 1.1            | 127 \pm 9                        | 0.40 \pm 0.11  |
| \( K^*(892)^+K^- + c.c. \) | 2.9_{-1.7}^{+1.3} \pm 0.4   | 50 \pm 4                         | 0.59_{-0.36}^{+0.27} |
| \( K^*(892)^0K^0 + c.c. \) | 13.3_{-2.8}^{+2.4} \pm 1.7 | 42 \pm 4                         | 3.2 \pm 0.8   |
| \( \omega\pi^0 \) | 1.87_{-0.62}^{+0.68} \pm 0.28 | 4.2 \pm 0.6                      | 4.4_{-1.6}^{+1.8} |
| \( \rho\eta \)    | 1.78_{-0.67}^{+0.66} \pm 0.17 | 1.93 \pm 0.23                    | 9.5_{-3.3}^{+3.6} |
| \( \rho\eta' \)   | 1.87_{-1.11}^{+1.04} \pm 0.33 | 1.05 \pm 0.18                    | 17.8_{-11.1}^{+15.9} |
| \( \phi\pi^0 \)   | < 0.41                         | < 0.068                         | –              |
| \( \phi\eta \)    | 3.3 \pm 1.1 \pm 0.5            | 6.5 \pm 0.7                      | 5.1 \pm 1.9   |
| \( \phi\eta' \)   | 2.8 \pm 1.5 \pm 0.6            | 3.3 \pm 0.4                      | 8.5 \pm 5.0   |
| \( \omega\eta \)  | < 3.2                          | 15.8 \pm 1.6                     | < 2.0         |
| \( \omega\eta' \) | 3.1_{-2.4}^{+2.4} \pm 0.7     | 1.67 \pm 0.25                    | 19_{-13}^{+15} |
| \( p\bar{p}\pi^0 \) | 13.2 \pm 1.0 \pm 1.5          | 10.9 \pm 0.09                    | 12.1 \pm 1.9  |
| \( p\bar{p}\eta \) | 5.8 \pm 1.1 \pm 0.7            | 2.09 \pm 0.18                    | 2.8 \pm 0.7   |
5 Analysis of $\psi(2S) \rightarrow p\bar{p}\pi^0(\eta)$

The final states of these two decay modes are the same $p\bar{p}\gamma\gamma$, and the signal event numbers are got by fitting the $\gamma\gamma$ invariant mass distribution in the selected events with $p\bar{p}\gamma\gamma$ final state. The branching fractions for $\psi(2S) \rightarrow p\bar{p}\pi^0$ and $\psi(2S) \rightarrow p\bar{p}\eta$ are listed in Table 2. For $\psi(2S) \rightarrow p\bar{p}\pi^0$, the errors are much smaller than the previous measurement by Mark-II. There are enhancements with $p\pi$ and $p\eta$ mass around 1.5 GeV, and weak evidences for the $p\bar{p}$ threshold enhancements in both channels.

6 Summary

We report the results on $\psi(2S)$ decays into 10 VP channels and $p\bar{p}\pi^0(\eta)$ final states. The branching fractions in our measurement are consistent with those of CLEO. With the measured branching fractions, the “12% rule” is tested. From the ratios $Q_h$ in Table 2 we see the channels of $p\eta$, $p\rho\eta'$, $p\phi\eta'$ and $p\bar{p}\pi^0$ are consistent with “12% rule”, while the others are suppressed. The solution to the ”$\rho\pi$ puzzle” seems to need more accurate measurements and further effort from theory.

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