Hadron Spectroscopy and Charmonium Decays from BES and CLEOc* [1)]

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Abstract Recent results from BES and CLEOc experiments on hadron spectroscopy and charmonium decays using J/ψ, ψ′ and ψ″ data samples collected in e^+e^- annihilation are reviewed, including the study of the scalar particles in J/ψ radiative and hadronic decays, as well as in ψ′ and χ_{c0} hadronic decays, and the study of the "ρπ puzzle" in J/ψ, ψ′, and ψ″ decays. The new results on the light scalars and the new information on the hadronic decays of the ortho-charmonium states shed light on the understanding of QCD.

Key words hadron spectroscopy, charmonium, QCD

1 Introduction

BES II [1] running at BEPC and CLEOc[2] running at CESR are the two detectors operating in the τ-charm energy region. Both experiments have collected large data samples of charmonium decays including 58M J/ψ events, 14M ψ′ events, and 33pb^{-1} data around ψ″ peak at BES II, and 4M ψ′ events, and 281pb^{-1} ψ″ events at CLEOc. To study the continuum background in the charmonium decays, special data samples at the center of mass energy lower than the ψ′ mass were taken both at BES II ($\sqrt{s}$ = 3.650GeV) and at CLEOc ($\sqrt{s}$ = 3.671GeV), the luminosities are 6.4pb^{-1} and 21pb^{-1} respectively. These data samples are used for the study of the hadron spectroscopy, the D decay properties and the CKM matrix, as well as the charmonium decay dynamics.

In this paper, we focus on the study of the properties of the scalars from J/ψ radiative and hadronic decays, from ψ′ hadronic decays, and from χ_{cJ} hadronic decays which is a new approach of studying the scalars; and the extensive study of the "ρπ puzzle" related physics in J/ψ, ψ′ and ψ″ decays.

It should be noted that performance of the CLEOc detector is much better than the BES II detector, especially in the photon detection, this makes the 4M ψ′ events data sample at CLEOc produces results with similar precision as from 14M ψ′ events from BES II.

2 Scalar particles in J/ψ, ψ′ and χ_{c0} decays

The study of the scalars is very important in two aspects: in experiment, there are still controversies about the resonance parameters of these states; and in theory, it is still hard to incorporate all the experimental results in a self-consistent picture. The reason for the former is somewhat due to the techniques used in extracting the physics information from the experimental data, namely, the partial wave analysis (PWA) was extensively used in the analyses, but

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sometimes it is rather arbitrary as to what resonance need to be included in the complicated fit with a few ten and even more than one hundred free parameters. The reason for the latter, in part is due to the fact that the experimental results may not all be reliable, and the complexity in the low energy QCD domain that the higher order terms neglected may not be small, and the mixing of the states in principle is hard to be considered completely.

2.1 Radiative and hadronic J/ψ decays

Using the world largest J/ψ data sample in e^+e^- annihilation experiment, BES studied the scalars decay into a pair of pseudoscalars ($\pi^+\pi^-$, $\pi^0\pi^0$, K^+K^- and $K^0_sK^0_s$) in J/ψ radiative decays as well as recoiling against a φ or an ω[3—6]. The full mass spectra and the scalar part in them are shown in Fig. 1.

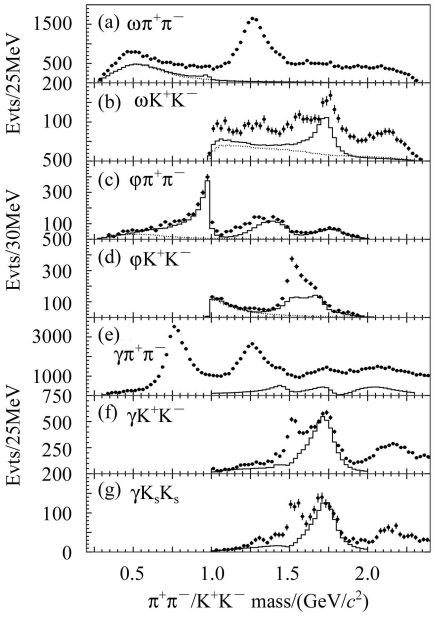

Fig. 1. The invariant mass distributions of the pseudoscalar meson pairs recoiling against ω, φ, or γ in J/ψ decays measured at BES Ⅱ. The dots with error bars are data, the solid histograms are the scalar contribution from PWA, and the dashed lines in (a) through (c) are contributions of σ from the fits, while the dashed line in (d) is the $f_0(980)$. Notice that not the full mass spectra are analyzed in (e), (f), and (g). Results in (e) are preliminary, otherwise are published.

From the analyses, BES sees significant contributions of σ particle in $\omega\pi^+\pi^-$ and ωK^+K^-, and also hint in $\phi\pi^+\pi^-$. Two independent partial wave analyses are performed on $\omega\pi^+\pi^-$ data and four different parameterizations of the σ amplitude are tried, all give consistent results for the σ pole, which is at $(541\pm39)-\mathrm{i}(252\pm42)\mathrm{MeV}/c^2$. There is also events accumulation in the low $\pi^+\pi^-$ mass in $\gamma\pi^+\pi^-$ mode, most probably due to the contribution of the σ, however, there is no attempt to analyze the structure at BES, one possible reason is the presentation of the huge background from $\rho^0\pi^0$. Nevertheless, the coupling of the σ with a photon in J/ψ decays is an important piece of information for the understanding of the nature of the particle, a better detector with more statistics may want to measure it.

Strong $f_0(980)$ is seen in $\phi\pi^+\pi^-$ and ϕK^+K^- modes, from which the resonance parameters are measured to be $M=965\pm8(\mathrm{stat})\pm6(\mathrm{syst})\mathrm{MeV}/c^2$, $g_1=165\pm10(\mathrm{stat})\pm15(\mathrm{syst})\mathrm{MeV}/c^2$ and $g_2/g_1=4.21\pm0.25(\mathrm{stat})\pm0.21(\mathrm{syst})$, where M is the mass, and g_1 and g_2 are the couplings to ππ and $K\bar{K}$ respectively if the $f_0(980)$ is parameterized using the Flatté's formula[7]. The production of $f_0(980)$ is very weak recoiling against an ω or a photon, which indicates that $s\bar{s}$ is the dominant component in it.

The $\phi\pi^+\pi^-$ data also show a strong scalar contribution at around $1.4\mathrm{GeV}/c^2$, it is due to the dominant $f_0(1370)$ interfering with a smaller $f_0(1500)$ component. The mass and width of $f_0(1370)$ are determined to be: $M=1350\pm50\mathrm{MeV}/c^2$ and $\Gamma=265\pm40\mathrm{MeV}/c^2$. In $\gamma\pi^+\pi^-$, a similar structure is observed in the same mass region, the fit yields a resonance at mass $1466\pm6(\mathrm{stat})\pm16(\mathrm{syst})\mathrm{MeV}/c^2$ with width of $108^{+14}_{-11}(\mathrm{stat})\pm21(\mathrm{syst})\mathrm{MeV}/c^2$, possibly the $f_0(1500)$, and the contribution from the $f_0(1370)$ can not be excluded. The production of $f_0(1370)$ and $f_0(1500)$ in $\gamma K\bar{K}$ is insignificant.

The K^+K^- invariant mass distributions from $\gamma K\bar{K}$ and ωK^+K^-, the $\pi^+\pi^-$ invariant mass distributions from $\gamma\pi^+\pi^-$ and $\phi\pi^+\pi^-$ show clear scalar contribution around $1.75\mathrm{GeV}/c^2$. Two states are resolved from the bump, one is $f_0(1710)$ with $M\sim1740\mathrm{MeV}/c^2$ and $\Gamma\sim150\mathrm{MeV}/c^2$ which decays to $K\bar{K}$ mostly, and one possible new state $f_0(1790)$ with $M\sim1790\mathrm{MeV}/c^2$ and $\Gamma\sim270\mathrm{MeV}/c^2$ which couples to ππ stronger than to $K\bar{K}$. However, the existence

of the second scalar particle needs confirmation: the signal observed in $\phi f_0(1790)$ is rather in the edge of the phase space, and the reconstruction efficiency of the ϕ decreases dramatically as the momentum of the ϕ decreases thus the momentum of the kaon from ϕ decays is very low and can not be detected. Furthermore, there are wide higher mass scalar states above $2\mathrm{GeV}/c^2$ as observed in $\gamma\pi^+\pi^-$ (Fig. 1(e)) and $\gamma\mathrm{K}\bar{\mathrm{K}}$[8], whose tails may interfere with the $f_0(1710)$ and produce structure near the edge of the phase space.

The use of these measurements for understanding the nature of the scalar particles can be found in Refs. [9—12], where the J/ψ decay dynamics and the fractions of the possible $\mathrm{q}\bar{\mathrm{q}}$ and glueball components in the states are examined.

2.2 Hadronic decays of ψ'

A measurement of the resonance parameters of σ using the BES Ⅱ $\psi' \to \mathrm{J}/\psi\pi^+\pi^-$ data sample gives similar pole position as measured in $\mathrm{J}/\psi \to \omega\pi^+\pi^-$[13]. Here a big destructive interference between the σ pole and the contact term is necessary to reproduce $\pi^+\pi^-$ mass distribution in the data sample.

2.3 Pair production of scalars in $\chi_{c0} \to \pi^+\pi^-\mathrm{K}^+\mathrm{K}^-$

Partial wave analysis of $\chi_{c0} \to \pi^+\pi^-\mathrm{K}^+\mathrm{K}^-$ is performed[14] using χ_{c0} produced in ψ' decays at BES Ⅱ. In 14M produced ψ' events, 1371 $\psi' \to \gamma\chi_{c0}$, $\chi_{c0} \to \pi^+\pi^-\mathrm{K}^+\mathrm{K}^-$ candidates are selected with around 3% background contamination.

Fig. 2(a) shows the scatter plot of $\mathrm{K}^+\mathrm{K}^-$ versus $\pi^+\pi^-$ invariant masses which provides further information on the intermediate resonant decay modes for $(\pi^+\pi^-)(\mathrm{K}^+\mathrm{K}^-)$ decay, while Fig. 2(b) shows the scatter plot of $\mathrm{K}^+\pi^-$ versus $\mathrm{K}^-\pi^+$ invariant masses for the resonances with strange quark.

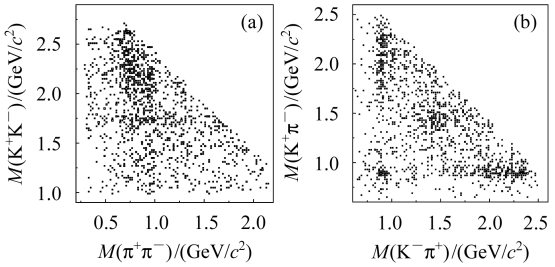

Fig. 2. The scatter plots of (a) $\mathrm{K}^+\mathrm{K}^-$ versus $\pi^+\pi^-$ and (b) $\mathrm{K}^+\pi^-$ versus $\mathrm{K}^-\pi^+$ invariant masses for selected $\psi' \to \gamma\chi_{c0}$, $\chi_{c0} \to \pi^+\pi^-\mathrm{K}^+\mathrm{K}^-$ events from BES Ⅱ.

Table 1. Summary of the $\chi_{c0} \to \pi^+\pi^-\mathrm{K}^+\mathrm{K}^-$ results, where X represents the intermediate decay modes, N^{fit} is the number of fitted events, and s.s. indicates signal significance.

decay mode (X)	N^{fit}	branching ratio (10^{-4}) $\mathscr{B}[\chi_{c0} \to \mathrm{X} \to \pi^+\pi^-\mathrm{K}^+\mathrm{K}^-]$	s.s.
$f_0(980)f_0(980)$	27.9 ± 8.7	$3.46 \pm 1.08^{+1.93}_{-1.57}$	5.3σ
$f_0(980)f_0(2200)$	77.1 ± 13.0	$8.42 \pm 1.42^{+1.65}_{-2.29}$	7.1σ
$f_0(1370)f_0(1710)$	60.6 ± 15.7	$7.12 \pm 1.85^{+3.28}_{-1.68}$	6.5σ
$\mathrm{K}^*(892)^0\bar{\mathrm{K}}^*(892)^0$	64.5 ± 13.5	$8.09 \pm 1.69^{+2.29}_{-1.99}$	7.1σ
$\mathrm{K}_0^*(1430)\bar{\mathrm{K}}_0^*(1430)$	82.9 ± 18.8	$10.44 \pm 2.37^{+3.05}_{-1.90}$	7.2σ
$\mathrm{K}_0^*(1430)\bar{\mathrm{K}}_2^*(1430) + \mathrm{c.c.}$	62.0 ± 12.1	$8.49 \pm 1.66^{+1.32}_{-1.99}$	8.7σ
$\mathrm{K}_1(1270)^+\mathrm{K}^- + \mathrm{c.c.}$ $\mathrm{K}_1(1270) \to \mathrm{K}\rho(770)$	68.3 ± 13.4	$9.32 \pm 1.83^{+1.81}_{-1.64}$	8.6σ
$\mathrm{K}_1(1400)^+\mathrm{K}^- + \mathrm{c.c.}$ $\mathrm{K}_1(1400) \to \mathrm{K}^*(892)\pi$	19.7 ± 8.9	< 11.9 (90% C.L.)	2.7σ

Besides $(\pi\pi)(\mathrm{KK})$ and $(\mathrm{K}\pi)(\mathrm{K}\pi)$ modes, $(\mathrm{K}\pi\pi)\mathrm{K}$ mode which leads to a measurement of $\mathrm{K}_1(1270)\mathrm{K}$ and $\mathrm{K}_1(1400)\mathrm{K}$ decay processes is also included in the fit. The PWA results are summarized in Table 1. From these results, we notice that scalar resonances have larger decay fractions compared to those of tensors, and such decays provide a relatively clean laboratory to study the properties of scalars, such as $f_0(980)$, $f_0(1370)$, $f_0(1710)$, and so forth. The upper limits of the pair production of the scalar mesons which are less significant are determined at the 90% C.L. to be

$$\mathscr{B}[\chi_{c0}\to f_0(1370)f_0(1370)]\mathscr{B}[f_0(1370)\to\pi^+\pi^-]\mathscr{B}[f_0(1370)\to K^+K^-]<2.9\times10^{-4},$$
$$\mathscr{B}[\chi_{c0}\to f_0(1370)f_0(1500)]\mathscr{B}[f_0(1370)\to\pi^+\pi^-]\mathscr{B}[f_0(1500)\to K^+K^-]<1.8\times10^{-4},$$
$$\mathscr{B}[\chi_{c0}\to f_0(1500)f_0(1370)]\mathscr{B}[f_0(1500)\to\pi^+\pi^-]\mathscr{B}[f_0(1370)\to K^+K^-]<1.4\times10^{-4},$$
$$\mathscr{B}[\chi_{c0}\to f_0(1500)f_0(1500)]\mathscr{B}[f_0(1500)\to\pi^+\pi^-]\mathscr{B}[f_0(1500)\to K^+K^-]<0.55\times10^{-4},$$
$$\mathscr{B}[\chi_{c0}\to f_0(1500)f_0(1710)]\mathscr{B}[f_0(1500)\to\pi^+\pi^-]\mathscr{B}[f_0(1710)\to K^+K^-]<0.73\times10^{-4}.$$

The above results supply important information on the understanding of the natures of the scalar states[15], as well as the decay dynamics of χ_{cJ} decays into pair of scalar particles.

2.4 Comments on the PWA

PWA is extensively used in extracting physics information from the experimental data, all the information listed above in this section are from PWA. While we know the PWA uses the information in the full phase space for physics study so that it is more powerful than working in one dimension (invariant mass, for example) or a bit higher dimension, it suffers from too many free parameters and other technical problems.

First of all, the experimental data are all affected by the finite resolution in momentum, energy, or direction measurement, this was not considered in current analyses; secondly, the parametrization of the resonance, especially the wide resonance, still have room to improve. Finally, the effect of the imperfect simulation of the detectors is hard to be considered in a fit with a few ten or even more free parameters. These effects may not be significant when the statistics is low, however, as the statistics increases, all these effects will possibly produce significant fake signals. How to handle these, if not now, at least in the near future, should be studied since high luminosity experiments will be soon available.

Studying the papers dealing with the PWA, it is found that two important information are missing in most of the analyses, which are the goodness-of-fit and the correlation coefficients between the fit out parameters.

In many of the analyses, the comparison to the alternative fits are given to show the fit is the best among all the fits tested, however this does not guarantee the fit used in the analysis is reliable. A simple example is, in fitting to a Gaussian distribution, using a 2nd order polynomial is better than using a straight line, but this does not mean the fit is acceptable. To give the goodness-of-fit is not easy in case of PWA since the fitting function is always very complicated. A possible way is to supply a simple χ^2 test in one or multi-dimension as has been done in Ref. [14], although not perfect, it shows the reader a feeling how the fit describes the data. Another possible way is try to use toy Monte Carlo to get the expected distribution of the χ^2 or the likelihood after generating many MC samples using the fit out parameters as input, and compare with the one got from the fit to the data — this may be a bit time consuming, however, it is more reliable than the χ^2-test since the detector effects are considered.

The parameters from the fit are generally correlated, and sometimes, some variables are highly correlated, in this case, only reporting the diagonal error is not enough. This is extremely important when there are two nearby resonances with strong interference, they are anti-correlated and one component will increase (decrease) as the other decreases (increases) to make the total contribution unchanged. Neglecting this in the theoretical analysis will also be dangerous. Another effect of the correlation is the significance of the signal may be affected strongly, that is, a declared significance may not be as high as that determined when there is no correlation, and vice versa.

3 "ρπ puzzle" in vector charmonia decay

From perturbative QCD (pQCD), it is expected that both J/ψ and ψ' decaying into light hadrons are dominated by the annihilation of $c\bar{c}$ into three gluons or one virtual photon, with a width proportional to

the square of the wave function at the origin[16]. This yields the pQCD "12% rule",

$$Q_{\rm h}=\frac{\mathscr{B}_{\psi'\to {\rm h}}}{\mathscr{B}_{{\rm J}/\psi\to {\rm h}}}=\frac{\mathscr{B}_{\psi'\to {\rm e^+e^-}}}{\mathscr{B}_{{\rm J}/\psi\to {\rm e^+e^-}}}\approx 12\%. \quad (1)$$

A large violation of this rule was first observed in decays to $\rho\pi$ and $K^{*+}K^-+$c.c. by Mark Ⅱ[17], known as the $\rho\pi$ puzzle, where only the upper limits on the branching fractions were reported in ψ' decays. Since then, many two-body decay modes of the ψ' have been measured by the BES collaboration and recently by the CLEO collaboration; some decays obey the rule while others violate it[8, 18, 19].

The extension of the above rule to ψ'' is straightforward, in the same scheme, one would expect

$$Q'_{\rm h}=\frac{\mathscr{B}_{\psi''\to {\rm h}}}{\mathscr{B}_{{\rm J}/\psi\to {\rm h}}}=\frac{\mathscr{B}_{\psi''\to {\rm e^+e^-}}}{\mathscr{B}_{{\rm J}/\psi\to {\rm e^+e^-}}}\approx 1.9\times 10^{-4}. \quad (2)$$

As the ψ'' data samples are available both at BESⅡ and CLEOc, the search for the decays of ψ'' into light hadrons was performed. Since ψ'' is above the charm threshold, it is expected the dominant decays of it is to charmed meson pairs, however, large fraction of charmless decays of ψ'' is expected if ψ'' is a mixture of S- and D-wave charmonium states and the mixing is responsible for the "12% rule" violation in J/ψ and ψ' decays. The above two rules may be tested by the large data samples of J/ψ, ψ', and ψ'' at both BESⅡ and CLEOc.

3.1 $\psi\to\rho\pi$: current status

The $\rho\pi$ mode of the vector charmonia decays is essential for this study, since this is the first puzzling channel found in J/ψ and ψ' decays. The new measurements, together with the old information, show us a new picture of the charmonium decay dynamics.

3.1.1 $J/\psi\to\pi^+\pi^-\pi^0$

BESⅡ measured the $J/\psi\to\pi^+\pi^-\pi^0$ branching fraction using its J/ψ and $\psi'\to J/\psi\pi^+\pi^-$ data samples[20], and BABAR measured the same branching fraction using J/ψ events produced by initial state radiative (ISR) events at $\sqrt{s}=10.58$GeV[21]. Together with the measurement from Mark-Ⅱ[17], we get a weighted average of $\mathscr{B}(J/\psi\to\pi^+\pi^-\pi^0)=(2.00\pm0.09)\%$.

To extract the $J/\psi\to\rho\pi$ branching fraction, PWA is needed to consider the possible contribution from the excited ρ states, the only available information on the fraction of $\rho\pi$ in $J/\psi\to\pi^+\pi^-\pi^0$ was got from Mark-Ⅲ. Using the information given in Ref. [22], we estimate $\frac{\mathscr{B}(J/\psi\to\rho\pi)}{\mathscr{B}(J/\psi\to\pi^+\pi^-\pi^0)}=1.17(1\pm10\%)$, with the error from an educated guess based on the information in the paper since we have no access to the covariant matrix from the fit showed in the paper. From this number and $\mathscr{B}(J/\psi\to\pi^+\pi^-\pi^0)$ got above, we estimate $\mathscr{B}(J/\psi\to\rho\pi)=(2.34\pm0.26)\%$. This is substantially larger than the world average listed by PDG[8], which is $(1.27\pm0.09)\%$.

3.1.2 $\psi'\to\pi^+\pi^-\pi^0$

$\psi'\to\rho\pi$ was studied both at BESⅡ[23] and CLEOc[19]. After selecting two charged pions and two photons, clear π^0 signals are observed in the two photon invariant mass spectra, the numbers of signals are found to be 229 and 196 from BESⅡ (shown in left plot of Fig. 3 as an example) and CLEOc respectively, and the branching fraction of $\psi'\to\pi^+\pi^-\pi^0$ is measured to be $(18.1\pm1.8\pm1.9)\times10^{-5}$ and $(18.8^{+1.6}_{-1.5}\pm1.9)\times10^{-5}$ at BESⅡ and CLEOc respectively. The two experiments give results in good agreement with each other. The Dalitz plot of $\psi'\to\pi^+\pi^-\pi^0$ events (right plot of Fig. 3) shows very different signature from that of $J/\psi\to\pi^+\pi^-\pi^0$ decays, there are lots of events in the center part of the Dalitz plot in the former case, while in the latter, almost all the events are in the ρ mass region and there is almost nothing in the center of the Dalitz plot.

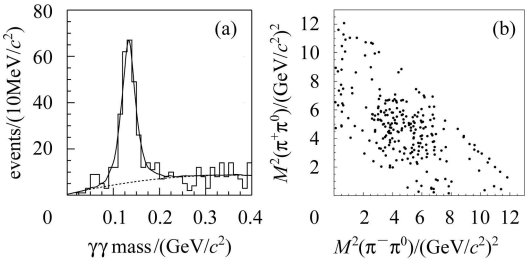

Fig. 3. Two photon invariant mass distribution (left) and the Dalitz plot (right) after final selection for BESⅡ ψ' data. The histograms are data, and the curves show the best fits.

To extract the branching fraction of $\psi'\to\rho\pi$, however, BESⅡ uses a PWA including the high mass ρ states and the interference between them, while

CLEOc counts the number of events by applying a ρ mass cut. The branching fraction from BES Ⅱ is $(5.1\pm0.7\pm1.1)\times10^{-5}$, while that from CLEOc is $(2.4^{+0.8}_{-0.7}\pm0.2)\times10^{-5}$, the difference is large. Although a big difference exists between the BES Ⅱ and CLEOc results, it does mean that the $\psi'\to\rho\pi$ signal exists, rather than the signal is completely missing as has been guessed before. If we take a weighted average neglecting the difference between the two measurements, we get $\mathscr{B}(\psi'\to\rho\pi)=(3.1\pm0.7)\times10^{-5}$.

Comparing $\mathscr{B}(\psi'\to\rho\pi)$ with $\mathscr{B}(J/\psi\to\rho\pi)$, one gets

$$Q_{\rho\pi}=\frac{\mathscr{B}(\psi'\to\rho\pi)}{\mathscr{B}(J/\psi\to\rho\pi)}=(0.13\pm0.03)\%.$$

The suppression compared to the 12% rule is obvious.

3.1.3　$\psi''\to\pi^+\pi^-\pi^0$

It has been pointed out that the continuum amplitude plays an important role in measuring ψ'' decays into light hadrons[24]. In fact, there are two issues which need to be clarified in ψ'' decays, that is whether ψ'' decays into light hadrons really exist, and if it exists, how large is it. By comparing the cross sections of $e^+e^-\to\pi^+\pi^-\pi^0$ at the ψ'' resonance peak ($\sqrt{s}=3.773$GeV) and at a continuum energy point ($\sqrt{s}=3.650$GeV at BES Ⅱ and 3.671GeV at CLEOc) below the ψ' peak, both BES Ⅱ and CLEOc found that $\sigma(e^+e^-\to\pi^+\pi^-\pi^0)$ at continuum is larger than that at ψ'' resonance peak. The average of the two experiments[25, 26] are

$$\sigma(e^+e^-\to\pi^+\pi^-\pi^0)_{\rm on} = 7.5\pm1.2\text{pb},$$
$$\sigma(e^+e^-\to\pi^+\pi^-\pi^0)_{\rm off} = 13.7\pm2.6\text{pb}.$$

The difference, after considering the form factor variation between 3.650 and 3.773GeV, is still significant, and it indicates that there is an amplitude from ψ'' decays which interferes destructively with the continuum amplitude, and makes the cross section at the ψ'' peak smaller than the pure contribution of continuum process.

For the ρπ mode, BES Ⅱ can only give upper limit of its cross section due to the limited statistics of the data sample, the upper limit at 90% C. L. is found to be 6.0pb[25] at the ψ'' peak, which is in consistent with the measurement from CLEOc using a much larger data sample: $(\sigma(e^+e^-\to\rho\pi)_{\rm on}=4.4\pm0.6\text{pb})$[26]; while the cross section at the continuum is $8.0^{+1.7}_{-1.4}\pm0.9$pb measured by CLEOc.

To extract the information on the $\psi''\to\rho\pi$ branching fraction, BES Ⅱ developed a method based on the measured cross sections at ψ'' resonance peak and at the continuum[25]. By neglecting the electromagnetic decay amplitude of ψ'', there are two amplitudes which contribute to the cross section at the ψ'' peak, the strong decay amplitude of ψ'' and the continuum amplitude. Taking the continuum amplitude as a real number, the ψ'' strong decay amplitude is described as one real number for the magnitude, and one phase between ψ'' strong and electromagnetic decays to describe the relative phase between the two amplitudes. Since only two measurements are available (at ψ'' peak and at continuum), one can only extract ψ'' decay branching fraction as a function of the relative phase. BES Ⅱ measurement on the upper limit of the $e^+e^-\to\rho\pi$ cross section at ψ'' peak, together with the CLEOc measurement of the continuum cross section restrict the physics region of the branching fraction and the relative phase as shown in Fig. 4(left). From the Figure, we see that the branching fraction of $\psi''\to\rho\pi$ is restricted within 6×10^{-6} and 2.4×10^{-3}, and the phase is between -150° and -20°, at 90% C.L.

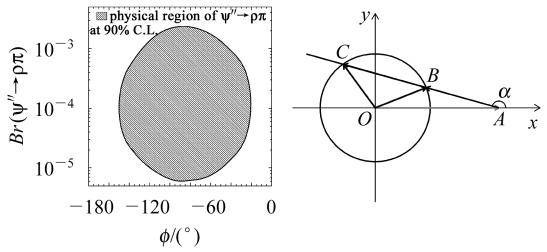

Fig. 4. Physics region on $\mathscr{B}(\psi''\to\rho\pi)$ and the relative phase (ϕ) between ψ'' strong and electromagnetic decays from BES Ⅱ (left); and the illustration of the two solutions in ψ'' decays (right): $\overrightarrow{OA}$ represents the continuum amplitudes, $\overrightarrow{OB}$ or $\overrightarrow{OC}$ represents the peak amplitudes, and $\overrightarrow{AB}$ and $\overrightarrow{AC}$ are the two solutions for the resonance decay amplitudes, α is the relative phase between continuum amplitude and the ψ'' strong decay amplitude, including the relative phase ϕ and the relative phase between continuum and ψ'' Breit-Wigner amplitudes.

The observation of the $e^+e^- \to \rho\pi$ signal at ψ'' peak and the measurement of the cross section[26] at CLEOc further make the physical region in the branching ratio and relative phase plane smaller: the CLEOc measurement gives a similar outer bound of the physical region as BES gives, while also indicates the central part of the physical region in Fig. 4(left) is not allowed by physics. By using a toy Monte Carlo to simulate the CLEOc selection criteria and the interference between the resonance and continuum amplitudes, we found that the $\psi'' \to \rho\pi$ branching fraction could be either $(2.1 \pm 0.3) \times 10^{-3}$ or $(2.4^{+3.4}_{-2.0}) \times 10^{-5}$ from the CLEOc measurements, if the relative phase between ψ'' strong and electromagnetic decay amplitudes is -90° as observed in J/ψ and ψ' decays[27].

The reason why there are two solutions for ψ'' decays can be understood as illustrated in Fig. 4(right). If we take the continuum amplitude as a real number, it can be shown as a vector along the real axis in the complex plane, the total cross section at ψ'' peak only gives the magnitude of the total amplitude and it is shown as a circle in the plot, the amplitude of the ψ'' decays, represented by a vector connecting the end of the continuum amplitude and the end of the total amplitude may have two cross points with the circle, representing the two solutions of the ψ'' decay amplitudes, and thus the branching fractions. Only in some very special cases, there is only one solution. The angle between the continuum amplitude and the ψ'' decay amplitudes is shown in the plot as α, it is the sum of the relative phase ϕ between the strong and electromagnetic decays of ψ'', and the phase from Breit-Wigner function for the ψ'' resonance. It can be seen that, the two solutions only happens when the cross section at continuum is larger than or equal to that at ψ'' peak; otherwise, there is only one solution, as in $\psi' \to \rho\pi$ case. However, as in physics, there is only one ψ'' decay branching fraction, there must be a way to extract the ψ'' decay branching fraction experimentally, this could be made possible if one more data sample is taken at a different energy point, for example, in the shoulder of the ψ'' resonance; furthermore, if one even wants to get the value of the relative phase, one more data point is necessary. In total, to get concrete physics information on the ψ'' decay branching fraction, at least data samples at four different energy points are needed, better have one point far from the resonance, so that it gives absolute measurement of the continuum amplitude. A detailed description can be found in Ref. [28].

Based on current data samples, one gets

$$Q'_{\rho\pi} = \frac{\mathscr{B}(\psi'' \to \rho\pi)}{\mathscr{B}(J/\psi \to \rho\pi)} = (9.0 \pm 1.6)\% \text{ or } (0.10^{+0.15}_{-0.09})\%,$$

to be compared with the pQCD prediction of 0.019% if ψ'' is pure D-wave charmonium.

3.2 Other studies and comments

There are many more new measurements on ψ' decays for the extensive study of the "12% rule"[8, 18, 19, 29], among which the Vector-Pseudoscalar (VP) modes are measured as first priority. The ratios of the branching fractions are all suppressed for these VP modes compared with the 12% rule. The multi-hadron modes and the Baryon-antibaryon modes are either suppressed, or enhanced, or normal, which are very hard to be categorized simply. The various models, developed for interpreting specific mode can hardly find solution for all these newly observed modes.

The ψ'' decays into light hadrons were searched for in various ψ'' decay modes, including VP and multi-hadron modes[26, 30]. However, only the comparison between the cross sections at continuum and those at ψ'' resonance peak are given, instead of giving the ψ'' decay branching fractions. In current circumstances, it is still not clear whether the ψ'' decays into light hadrons with large branching fractions, since, as has been shown in the $\rho\pi$ case, there could be two solutions for the branching fraction, and the two values could be very different.

As the luminosity at the ψ'' peak is large enough, current study is limited by the low statistics at the continuum: at CLEOc, the luminosity at continuum is more than an order of magnitude smaller than that at peak, this prevents from a high precision comparison between the cross sections at the two energy points. One conclusion we can draw from the existing data is that the measurements do not contradict with

the assumption that the relative phase between ψ'' strong and electromagnetic decay amplitudes is around $-90°$, and the ψ'' decays into light hadrons could be large.

The study of the $\rho\pi$ puzzle between ψ' and J/ψ decays and the charmless decays of ψ'' should not be isolated as they were since J/ψ, ψ' and ψ'' are all charmonium states with very similar quantum numbers, and it is expected ψ' and ψ'' are the mixtures of 2S and 1D states[31]. In developing models to solve one of the problems, the others should also be considered. There have been a few models developed following this line or can be easily extended to all these three states, like the S- and D-wave charmonia mixing model[31], the $D\bar{D}$ re-annihilation in ψ''[32], the four-quark component in ψ''[33], and survival $c\bar{c}$ in ψ'[34], and so on. Experimentally testable predictions are welcome for validating the models.

One further observation is that many of the attempts to interpret the $\rho\pi$ puzzle are based on the potential models for the charmonium which were developed more than 20 years ago, as the B-factories discovered many new charmonium states[35] which are hard to be explained in the potential models, it may indicate even the properties of J/ψ, ψ' and ψ'' are not as expected from the potential models. The further understanding of the other high mass charmonium states may shed light on the understanding of the low lying ones.

4 Summary

There are many new results on hadron spectroscopy from the charmonium decays from BES Ⅱ and CLEOc experiments. While many analyses supply more information on the known states like the light scalar particles to understand the nature of them, there are also new observations which may indicate there is still something unexpected in the low energy regime. The decay properties of the vector charmonium states, have been studied for more than three decades, but they are still far from being understood, one extreme example is the "$\rho\pi$ puzzle" in J/ψ and ψ' decays. Further studies of all these are expected from the BESⅢ at BEPC Ⅱ which will start its data taking in 2007.

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References

1 BAI J Z et al(BES Collaboration). Nucl. Instrum. Methods, 1994, **A344**: 319; 2001, **A458**: 627
2 CLEO-c Collaboration. CLEO-c and CESR-c: A New Frontier of Weak and Strong Interactions: CLNS 01/1742
3 ABLIKIM M et al(BES Collaboration). Phys. Lett., 2004, **B598**: 149
4 ABLIKIM M et al(BES Collaboration). Phys. Lett., 2004, **B603**: 138
5 ABLIKIM M et al(BES Collaboration). Phys. Lett., 2004, **B607**: 243
6 BAI J Z et al(BES Collaboration). Phys. Rev., 2003, **D68**: 052003
7 Flatté S M. Phys. Lett., 1976, **B63**: 224
8 Eidelman S et al(Particle Data Group). Phys. Lett., 2004, **B592**: 1
9 Roca L et al. Nucl. Phys., 2004, **A744**: 127
10 Bugg D. hep-ex/0510021 Talk at the 11th International Conference on Hadron Spectroscopy. Aug. 21-26, 2005, Rio de Janeiro, Brazil
11 Close F, ZHAO Q. Phys. Rev., 2005, **D71**, 094022
12 ZHAO Q, ZOU B S, MA Z B. Phys. Lett., 2005, **B631**: 22
13 ZHU Y S (BES Collaboration). Talk at the 11th International Conference on Hadron Spectroscopy. Aug. 21-26, 2005, Rio de Janeiro, Brazil
14 ABLIKIM M et al(BES Collaboration). Phys. Rev., 2005, **D72**: 092002
15 ZHAO Q. Phys. Rev., 2005, **D72**: 074001
16 Appelquist T, Politzer H D. Phys. Rev. Lett., 1975, **34**: 43; De Rújula A, Glashow S L. Phys. Rev. Lett., 1975, **34**: 46
17 Franklin M E B et al(Mark Ⅱ Collaboration). Phys. Rev. Lett., 1983, **51**: 963
18 BAI J Z et al(BES Collaboration). Phys. Rev., 2004, **D69**: 072001; Phys. Rev. Lett., 2004, **92**: 052001; ABLIKIM M et al(BES Collaboration). Phys. Rev., 2004, **D70**: 112007; Phys. Rev., 2004, **D70**: 112003; Phys. Lett., 2005, **B614**: 37
19 Adam N E et al(CLEO Collaboration). Phys. Rev. Lett., 2005, **94**: 012005
20 BAI J Z et al(BES Collaboration). Phys. Rev., 2004, **D70**:

012005
21 Aubert B et al(BABAR Collaboration). Phys. Rev., 2004, **D70**: 072004
22 MARK-III Collaboration, CHEN L, Dunwoodie W M. In Proceedings of Hadron 91 Conference. College Park, Maryland, 1991. 100, SLAC-PUB-5674 (1991)
23 ABLIKIM M et al(BES Collaboration). Phys. Lett., 2005, **B619**: 247
24 WANG P, MO X H, YUAN C Z. Phys. Lett., 2003, **B574**: 41
25 ABLIKIM M et al(BES Collaboration). Phys. Rev., 2005, **D72**: 072007
26 Adams G S et al(CLEO Collaboration). hep-ex/0509011
27 WANG P, YUAN C Z, MO X H. Phys. Rev., 2004, **D69**: 057502
28 WANG P, MO X H, YUAN C Z. hep-ph/0512329
29 ABLIKIM M et al(BES Collaboration). Phys. Rev., 2005, **D71**: 072006; Briere R A et al(CLEO Collaboration). Phys. Rev. Lett., 2005, **95**: 062001; Pedlar T K et al(CLEO Collaboration). Phys. Rev., 2005, **D72**: 051108(R); MO X H (BES Collaboration). Talk at the 11th International Conference on Hadron Spectroscopy. Aug. 21-26, 2005, Rio de Janeiro, Brazil
30 HUANG G S et al(CLEO Collaboration). hep-ex/0509046
31 Rosner J L. Phys. Rev., 2001, **D64**: 094002
32 Rosner J L. hep-ph/0405196
33 Voloshin M. Phys. Rev., 2005, **D71**: 114003
34 Artoisenet P, Gerard J M, Weyers J. Phys. Lett., 2005, **B628**: 211; Gérard J M, Weyers J. Phys. Lett., 1999, **B462**: 324
35 Seth K K. Talk at the 11th International Conference on Hadron Spectroscopy. Aug. 21-26, 2005, Rio de Janeiro, Brazil

BES和CLEOc强子谱和粲偶素衰变研究*

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摘要 回顾了近期BES和CLEOc利用正负电子对撞机采集的J/ψ, ψ'和ψ''数据得到的强子谱与粲偶素衰变方面的部分研究结果. 重点分析了对于轻标量粒子的实验研究, 包括利用J/ψ的辐射衰变和强衰变, ψ'的强衰变和χ_c的强衰变得到的结果, 并对有关粒子的性质进行了评述, 对用以获得这些信息的实验方法作了评论, 提出了改进的建议; 还重点总结了矢量粲偶素粒子衰变"$\rho\pi$疑难"相关的实验和理论研究成果, 并对进一步的实验和理论研究提出了建议. 这些结果对于理解量子色动力学在低能区的应用有很大帮助.

关键词 强子谱 粲偶素 量子色动力学

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