Radiative decay of the $\psi(2s)$ into Two Pseudo-scalars

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We used $\sim 3.79 \times 10^6$ $\psi(2s)$ data collected by the BES detector to study the radiative decay of $\psi(2s)$ into $\pi\pi$, $K\overline{K}$ and $\eta\eta$. Branching fractions or upper limit of branching fractions of $\psi(2s)$ decay into $\gamma f_2(1270)$, $\gamma f_J(1710)$ as well as χ_{c0} and χ_{c2} decay into $\pi^0\pi^0$ and $\eta\eta$ have been determined. The results are consistent with the theoretical prediction according to the corresponding J/ψ decay modes.

I. MOTIVATION

In perturbative QCD, the dominant process of J/ψ and $\psi(2s)$ hadronic decay is through the $c\overline{c}$ annihilation into three gluons. Since the decay width is proportion to the amplitude of the $c\overline{c}$ wave function at origin, $|\Psi(0)|^2$, it is reasonable to expect that the branching fractions of J/ψ and $\psi(2s)$ decay into any non-charmonium states are linked as [1]:

$$Q = \frac{B(\psi(2s) \to h)}{B(J/\psi \to h)} = \frac{B(\psi(2s) \to ggg)}{B(J/\psi \to ggg)}$$
$$\simeq \frac{B(\psi(2s) \to e^+e^-)}{B(J/\psi \to e^+e^-)} = (14.6 \pm 2.2)\%$$

This relation is sometimes referred to as *the 15% rule*. The prediction was originally made for the total decay width through three gluons. Since the partial width of individual channels involving the initial annihilation of $c\overline{c}$ quarks are also functions of the $|\Psi(0)|^2$, we expect this rule generally valid for these individual decay processes, though it may not be followed perfectly due to many other factors that are not considered here.

Results from the Mark II experiment [2] show that while many of the $\psi(2s)$ hadronic decay channels obey this rule, it is severely violated in vector plus pseudo-scalar (VP) final states such as $\rho\pi$ and $K^*\overline{K}$ — the so called $\rho\pi$ *puzzle*. Recently the BES experiment also reported heavy suppression in the vector plus tensor (VT) final states such as $K^*\overline{K_2^*}$, ρa_2, ωf_2 and $\phi f_2^{'}$ [3] as well as some of the axial-vector plus pseudo-scalar (AP) modes such as $K_1^{\pm}(1270)K^{\mp}$ [4].

The dominate process of J/ψ and $\psi(2s)$ radiative are similar to their hadronic decay into three gluons in that one of the gluon line is replaced by a radiative photon, which in turn replace one of the α_S by α_{QED} in the cross section formula. So it is expected that the *15% rule* should also work for radiative decay modes [5]. It is our interests to look at this kind of final states and see whether the relationship is broken or not. In this studying, through the analysis of $\psi(2s)$ radiative decay into $\pi\pi$, $K\overline{K}$ and $\eta\eta$, we report the first branching fraction measurement of $\psi(2s)$ radiative decay into $f_2(1270)$ and $f_J(1710)$, along with the measurement of χ_{c0} and χ_{c2} decay into $\pi\pi$ and $\eta\eta$ branching fractions.

II. THE BES DETECTOR

The $(3.79 \pm 0.31) \times 10^6$ of $e^+e^- \to \psi(2s)$ data we used for this analysis report was taken by the BES detector running on the BEPC storage ring. Detail description of the BES detector can be found in elsewhere [6]. It features a 40-layer main drift chamber (MDC) in a 0.4 T solenoidal magnetic field providing momentum resolution of $\sigma_p/p = 1.7\%\sqrt{1+p^2(GeV/c)}$ and dE/dx resolution of 9% for hadron tracks. Outside of the MDC cylinder is an array of 48 scintillation counter time-of-flight (TOF) system with 450 ps resolution for hadrons. A 24-layer lead-gas barrel electromagnetic calorimeter (BSC) resides outside of TOF provides a energy resolution of $\sigma_E/E = 0.22/\sqrt{E(GeV)}$ and spatial resolution of $\sigma_\phi = 4.5mrad$ and $\sigma_\theta = 12mrad$. There is also a 3-layer μ counter outside of the steel plates of magnetic flux return which is used to veto tracks with many hits in μ counter.

In this analysis, we only use photons hit at BSC but outside of its rib region. Showers whose direction are within 8^o are regarded as split showers and their energy are combined. In case a photon decay from a π^0 or η, the photon's helicity angle should satisfy $|cos\theta_{helicity}| < 0.99$ in order to remove fake photon. For charged tracks, we only used those within polar angle region $|cos\theta| < 0.8$. Charged track consistent with being elections/position in EM calorimeter or being μ^+ or μ^- in μ counter are rejected. TOF information, dE/dx information and kinematic fit are used for particle identification. Kinematic fit also serve the purpose of refining momentum measurements and mass resolutions as well as selecting combinations.

III. RESULTS FROM $\psi(2S) \to \gamma\pi\pi$

We looked at two channels here: $\psi(2s) \to \gamma\pi^+\pi^-$ and $\psi(2s) \to \gamma\pi^0\pi^0$. In case of the first channel, we select events with two oppositely charged tracks and at least one photon. TOF, dE/dx and kinematic fit information are combined and the total probability for being two pions should be lager the 1% and should also be larger than the total probability of being two kaons. The solid-line histogram of Fig. 1 shows invariant mass of $\pi^+\pi^-$ below 3 GeV. We can see an obvious ρ signal and also continuous background which is due to the initial state radiation process of $e^+e^- \to \gamma\rho$ and $e^+e^- \to (\gamma)\mu^+\mu^-$. This background can also be seen in the dash-line histogram of Fig. 1 from the $e^+e^- \to \tau\tau$ data taken by BES. In order to remove these background, we combine those events that past the final event selection criteria from both $\psi(2s)$ sample and τ sample together and assign each $\psi(2s)$ event a weight of 1 and each τ event a weight of $-w$ in the likelihood function for the mass fit. Here w is the ratio of the integrated luminosities of these two data sets. The result is shown in Fig. 2a. The data point in the plot are the result after the two histograms are normalized and subtracted.

Fig 2b is the result of the second channel — $\psi(2s) \to \gamma\pi^0\pi^0 \to \gamma\gamma\gamma\gamma\gamma$. We select events with at least 5 neutral tracks and no charged tracks. We apply a six-constraint fit over all possible $\gamma\pi^0\pi^0$ combinations with two π^0 resonants. We select the combination with smallest fitting χ^2 and also satisfy $M_{\gamma\gamma} = M_{\pi^0} \pm 70MeV$ (from a no π^0 resonant four-constraint fit) in the same time.

On both plots the $f_2(1270)$ signal are clear. We fit both plots with a D-wave Breit-Wigner function with $f_2(1270)$ mass and width fixed at the PDG values ($M_{f_2(1270)} = 1275MeV$ and $\Gamma_{f_2(1270)} = 185MeV$). A S-wave Breit-Wigner with mass and width fix at PDG values of $f_J(1710)$ has also been included in the mass fitting in $\gamma\pi^+\pi^-$ channel in order to describe the line shape in that region. A phase space background was included in the mass fit of $\gamma\pi^0\pi^0$ channel to describe the background underneath of the rather broad signal of $f_2(1270)$. We determined that there are 209.8 ± 23.1 events and 29.9 ± 11.1 events in Fig. 2a and Fig. 2b respectively.

Using the total of $(3.79 \pm 0.31) \times 10^6$ of $\psi(2s)$ events and the detector efficiency of 43.8% and 9.6% for $\gamma\pi^+\pi^-$ and $\gamma\pi^0\pi^0$ respectively obtained by using Monte Carlo simulate, we determined a branching fraction of $B(\psi(2s) \to \gamma f_2(1270)) = (2.31 \pm 0.25 \pm 0.42) \times 10^{-4}$ from the $\psi(2s) \to \gamma\pi^+\pi^-$ channel and $B(\psi(2s) \to \gamma f_2(1270)) = (3.01 \pm 1.12 \pm 1.12) \times 10^{-4}$ from $\psi(2s) \to \gamma\pi^0\pi^0$ channel, and a combined result from these two channels:

$$B(\psi(2s) \to \gamma f_2(1270)) = (2.37 \pm 0.25 \pm 0.39) \times 10^{-4}$$

The first error is statistical and the second is systematic. The latter includes uncertainties from major cuts, the shape of the background, the error from $\psi(2s)$ total number. This result, when compare with similar branching fraction from J/ψ decay on PDG, is consistent with the "15%" theoretical prediction.

The region where $\pi^+\pi^-$ invariant mass is higher than 3GeV has been looked at by another BES papar [7]. In our studying, we also looked at the invariant mass distribution of $\pi^0\pi^0$ by using the same event selection criteria described above. The $\pi^0\pi^0$ invariant mass in Fig. 3a clearly shows signals of χ_{c0} and χ_{c2}. We fit the mass plots with two Breit-Wigners plus polynomial background function and we determined 96.9 ± 11.1 and 20.8 ± 5.8 events for χ_{c0} and χ_{c2} respectively, and:

$$B(\chi_{c0} \to \pi^0\pi^0) = (2.80 \pm 0.32 \pm 0.6) \times 10^{-3}$$

$$B(\chi_{c2} \to \pi^0\pi^0) = (9.2 \pm 2.7 \pm 5.3) \times 10^{-4}$$

IV. RESULT FROM $\psi(2S) \to \gamma K\overline{K}$

In the $\psi(2s) \to \gamma K^+K^-$ channel, we used analyzing technology that is similar to what is used in $\psi(2s) \to \gamma\pi^+\pi^-$ except that we now ask the probability of two kaons' hypotheses from particle identification information should be larger than 0.01 and should also be larger than the probability of two pions' hypotheses. Similar QED background such as $e^+e^- \to \gamma\phi \to \gamma K^+K^-$ and $e^+e^- \to \gamma\mu^+\mu^-$ can be seen in Fig. 4 as dashed histogram. They are removed by using the BES τ scan data by assigning negative weight to τ events in the mass fit likelihood function. The $f_J(1710)$ signal is observed along with a possible signal of $f_2^{'}(1525)$ (Fig. 5). We fit the data point using a S-wave Breit-Wigner with mass and width fix at 1712 MeV and 133 MeV from PDG. We also include background contribution from $f_2^{'}(1525)$ by adding a D-wave Breit-Wigner into the fitting function. We determinated that there are 76.1 ± 12.0 events underneath the $f_J(1710)$ signal and a branching fraction:

$$B(\psi(2s) \to \gamma f_J(1710) \to \gamma K\overline{K}) = (1.24 \pm 020 \pm 0.16) \times 10^{-4}$$

The systematically error, which is the second error in the expression, includes uncertainties from major cuts, the error from $\psi(2s)$ total number and the uncertainty from the possible 2^{++} spin-parity hypotheses of $f_J(1710)$. This result is again consistent with the "15%" rule.

For the $\psi(2s) \to \gamma K_S^0 K_S^0 \to \gamma\pi^+\pi^-\pi^+\pi^-$ channel, we started with events with two positive charge tracks and two negative charge tracks and at least one photon. We required that both K_S^0 vertex can be reconstructed and $|M_{\pi^+\pi^-} - M_{K_S^0}| < 20MeV$. At least one of the combinations should pass a four-constraint fit with χ^2 probability larger than 0.01. If there are more than one combinations, we select the combination with smallest value of

$$\sqrt{(m_{\pi_1^+\pi_2^-} - m_{K_S^0})^2 + (m_{\pi_3^+\pi_4^-} - m_{K_S^0})^2}$$

A simple S-wave Breit Wigner plus polynomial background has been used to fit the invariant mass in Fig. 5b. It results in an upper limit of 10.8 events at 90% confidential level and an upper limit of branching fraction:

$$B(\psi(2s) \to \gamma f_J(1710) \to \gamma K\overline{K}) < 1.39 \times 10^{-4} \ \ (90\% \ C.L.)$$

which is consistent with the previous branching fraction obtained from $\psi(2s) \to \gamma K^+K^-$ channel.

V. RESULT FROM $\psi(2S) \to \gamma\eta\eta$

Event selection from this channel is harder than selecting $\gamma\pi^0\pi^0$ final state because the two photons decay from an η has a relatively large opening angle so it is harder to take the advantage of the good spatial resolution of the BES calorimeter. The selection criteria for this channel is similar to those used in $\psi(2s) \to \gamma\pi^0\pi^0$ channel except that we required $M_{\gamma\gamma} = M_\eta \pm 70MeV$. We can't identify any signals in the region where $M_{\eta\eta} < 3GeV$. In region where $M_{\eta\eta} > 3GeV$ in Fig. 3b, We see a χ_{c0} signal and a weak χ_{c2} signal. We used two Breit-Wigner functions with polynomial background to fit the mass plot and determined 12.7 ± 5.3 events of χ_{c0} and an upper limit of 5.9 χ_{c2} events as well as the following branching fractions:

$$B(\chi_{c0} \to \eta\eta) = (2.03 \pm 0.84 \pm 0.61) \times 10^{-3}$$

$$B(\chi_{c2} \to \eta\eta) < 2.0 \times 10^{-4} \ \ (90\% \ C.L.)$$

Flavor SU(3) symmetry indicated that the branching fraction of χ_{c0} decay into $\pi^0\pi^0$ and $\eta\eta$ should be the same except from a phase space factor and a barrier factor which is $p^(2s+1)$ where p is the momentum of the π^0 or η in χ_c's rest frame and s is the spin of χ_c's. In our studying, we determined:

$$\frac{B(\chi_{c0} \to \eta\eta)}{B(\chi_{c0} \to \pi^0\pi^0)} = 0.73 \pm 0.31 \pm 0.27$$

which is consistent with the theoretical prediction of 0.95 based on the flavor SU(3) symmetry.

VI. SUMMARY

In the papar we report the first measurement of $\psi(2s) \to \gamma f_2(1270)$ and $\psi(2s) \to \gamma f_J(1710) \to \gamma K\overline{K}$ branching fractions by looking at the $\psi(2s) \to \gamma\pi^+\pi^-$, $\gamma\pi^0\pi^0$, γK^+K^-, $\gamma K_S^0 K_S^0$ and $\gamma\eta\eta$ final states. The results are consistent with the "15%" theoretical prediction. In addition, we also report the first measure of the branching fractions of χ_{c0} and χ_{c2} decay into $\pi^0\pi^0$ and χ_{c0} decay into $\eta\eta$ as well as an upper limit of branching fraction of χ_{c2} decay into $\eta\eta$. The results from $\chi_{c0} \to \pi^0\pi^0$ and $\eta\eta$ are consistent with the flavor SU(3) symmetry.

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[1] W.S. Hou and A. Soni, Phys. Rev. lett. 50, 569(1980); G. Karl and W. Roberts, Phys. Lett. 144B, 243(1984); S.J. Brodsky *et al.*, Phys. Rev. Lett/ 59, 621(1987); M. Chaichian *et al.*, Nucl. Phys. B323, 75(1989); S.S Pinsky, Phys. Lett. B 236, 479(1990); X.Q. Li *et al.*, Phys. Rev. D 55, 1421(1997); S.J. Brodsky and M. Karliner, Phys. Rev. lett. 78, 4682(1997); Yu-Qi Chen and Eric Braaten, Phys. Rev. Lett. 80, 5060(1998).

[2] M.E.B. Franklin et al., Phys. Rev. Lett. 51, 11(1983).

[3] BES Collaboratoin, J.Z. Bai *et al.*, Phys. Rev. Lett. 81,5080(1998)

[4] BES Collaboratoin, J.Z. Bai *et al.*, Submitted to Phys. Rev. Lett.

[5] T. Appelquist, A. De Rújula, H.D. Politzer. S.L. Glashow. Phys. Rev. Lett. 3.4 (1975) 363; M. Chanowitz. Phys. Rev. D 12(1975) 918; L. Okun and M. Voloshin, ITEP-95-1976(unpublished); S.J. Brodsky, T.A. DeGrand, R.R. Horgun, D.G. Coyne, Phys. Lett. 73B (1978) 203; K. Koller and T. Walsh. Nucl. Phys. B140 (1978) 449.

[6] BES Collaboratoin, J.Z. Bai *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A 344, 319(1994)

[7] BES Collaboratoin, J.Z. Bai *et al.*, Phys. Rev. Lett. 81,3091(1998)

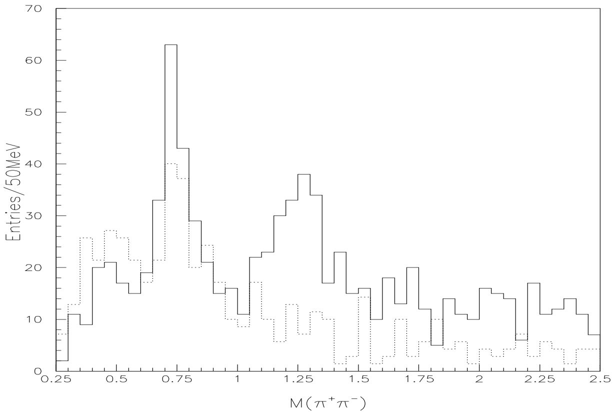

FIG. 1. $M_{\pi^+\pi^-}$ from $\psi(2s)$ data in the solid-line histogram and luminosity normalized τ data in the dash-line histogram

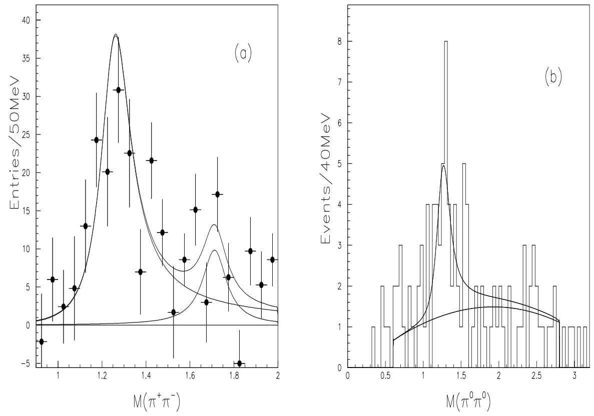

FIG. 2. (a): $M_{\pi^+\pi^-}$ fitting result. The data point is difference of the two histograms in Fig. 1 (b): $M_{\pi^0\pi^0}$

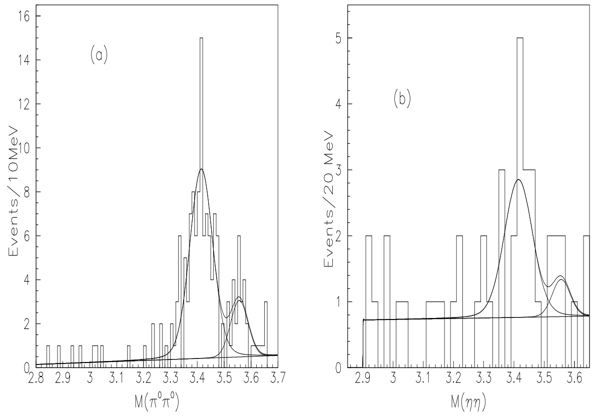

FIG. 3. Invariant mass of (a) $\pi^0\pi^0$ and (b) $\eta\eta$

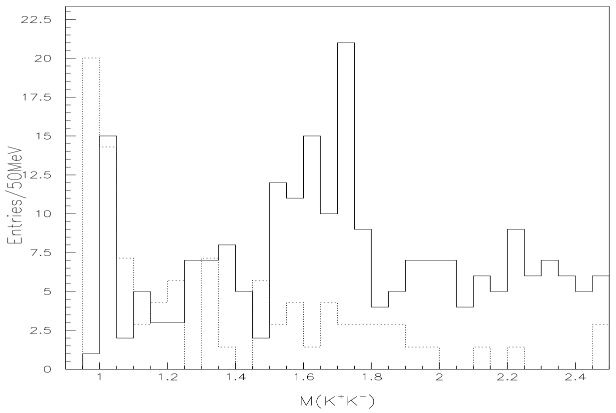

FIG. 4. $M_{K^+K^-}$ from $\psi(2s)$ data in the solid-line histogram and luminosity normalized τ data in the dash-line histogram

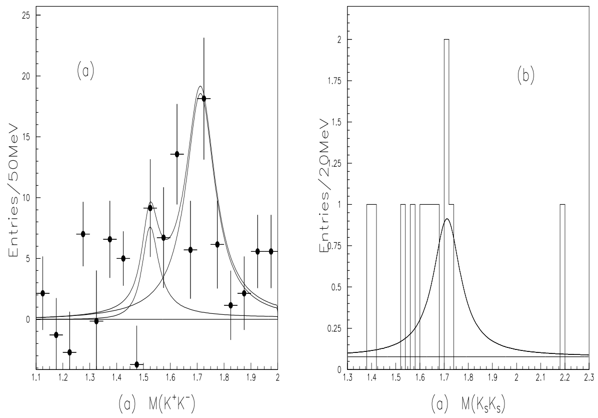

FIG. 5. Invariant mass of (a) K^+K^- and (b) $K_S^0K_S^0$. The data point in (a) is the difference of the two histograms in Fig. 4