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

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Radiative decays of the radially exited charmonium resonance, $\psi(2S)$, into $\pi\pi$, $K\overline{K}$ and $\eta\eta$ final states have been measured in a sample of $\sim 3.79 \times 10^6$ $\psi(2S)$ events collected by the BES collaboration. Branching fractions or upper limits of $\psi(2S)$ decays into non-charmonium final states $\gamma f_2(1270)$ and $\gamma f_J(1710)$ and into charmonium final states $\gamma\chi_{c0}$ and $\gamma\chi_{c2}$ have been determined. The $\psi(2S)$ radiative decay results in $\gamma f_2(1270)$ and $\gamma f_J(1710)$ channels follow the pattern of J/ψ decays.

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 proportional to the amplitude of the $c\overline{c}$ wave function at the origin, $|\Psi(0)|^2$, it is expected that the branching fractions of J/ψ and $\psi(2S)$ decay into light quark states are related 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 The prediction was originally made for the total decay width into three gluons.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 to be 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 $K^*\overline{K_2^*}$, $\rho a_2, \omega f_2$ 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 radiative J/ψ and $\psi(2S)$ decays are similar to their hadronic decays into three gluons except that one of the gluon lines is replaced by a radiative photon. The result leads to changing one power of the coefficient 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]. In the paper we explore this prediction for radiative decays. In this study of $\psi(2S)$ radiative decays 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 $(3.79 \pm 0.31) \times 10^6$ $e^+e^- \rightarrow \psi(2S)$ event data sample used for this analysis report was taken by the BES detector operating at the BEPC storage ring. Detailed description of the BES detector can be found 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) outside of the TOF system provides an energy resolution of $\sigma_E/E = 0.22/\sqrt{E(GeV)}$, spatial resolution of $\sigma_\phi = 4.5\ mrad$ and $\sigma_\theta = 12\ mrad$. There is also a 3-layer μ counter outside of the steel plates of the magnetic flux return which is identify and reject μ tracks.

In this analysis, we only use photons that shower in the BSC but outside of its aluminum support bar region. Showers whose direction are within 8^o are regarded as split showers and their energy are recombined. For a π^0 or η candidate that decays into two photons, the photon's helicity angle should be flat and hence asymmetric background decays can be removed by requiring $|cos\theta_{helicity}| < 0.99$. For charged tracks, we only used those within polar angle region $|cos\theta| < 0.8$. Charged tracks consistent with being electrons or positrons in the 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 fits are also used to improve momentum measurements and mass resolutions as well as selecting particular combinations if more than one is possible.

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

We studied two channels: $\psi(2S) \rightarrow \gamma\pi^+\pi^-$ and $\psi(2S) \rightarrow \gamma\pi^0\pi^0$. For the first channel, events are selected 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 larger than 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 and a clear ρ signal is observed over a continuous background which is due to the initial state radiation process of $e^+e^- \rightarrow \gamma\rho$ and $e^+e^- \rightarrow (\gamma)\mu^+\mu^-$. This background can also be seen in the dash-line histogram of Fig. 1 from the $e^+e^- \rightarrow \tau\tau$ data taken by BES. In order to remove these backgrounds, those events that pass the final event selection criteria from both $\psi(2S)$ sample and τ sample are used. In the fit, each $\psi(2S)$ event is assigned 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, $\psi(2s) \rightarrow \gamma\pi^0\pi^0 \rightarrow \gamma\gamma\gamma\gamma\gamma$. 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 resonances. We select the combination with the smallest fit χ^2 and that also satisfies $M_{\gamma\gamma} = M_{\pi^0} \pm 70MeV$ (from a four-constraint fit that does not include the π^0 mass constraint).

On both plots the $f_2(1270)$ signals 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 find 209.8 ± 24.9 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, determined from Monte Carlo simulation, of 43.8% and 9.6% for the $\gamma\pi^+\pi^-$ and $\gamma\pi^0\pi^0$ channels respectively, we determined a branching fraction of $B(\psi(2s) \rightarrow \gamma f_2(1270)) = (2.31 \pm 0.27 \pm 0.39) \times 10^{-4}$ from the $\psi(2S) \rightarrow \gamma\pi^+\pi^-$ channel and $B(\psi(2s) \rightarrow \gamma f_2(1270)) = (3.01 \pm 1.12 \pm 1.12) \times 10^{-4}$ from $\psi(2S) \rightarrow$

$\gamma\pi^0\pi^0$ channel, and a combined result from these two channels:

$$B(\psi(2S) \to \gamma f_2(1270)) = (2.37 \pm 0.26 \pm 0.37) \times 10^{-4}$$

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

Also in Fig. 2a, the number of events under the $f_J(1710)$ signal is 39.2 ± 10.1. The Monte Carlo determined efficiency for this channels is 45.4%. We thus have,

$$B(\psi(2S) \to \gamma f_J(1710) \to \gamma\pi\pi) \\ = (3.51 \pm 0.90 \pm 1.46) \times 10^{-5}$$

The region $\pi^+\pi^-$ invariant mass greater than 3 GeV has been investigated in another BES paper [7]. Here, we investigated the higher $\pi^0\pi^0$ mass distribution by using the same event selection criteria described above. The $\pi^0\pi^0$ invariant mass in Fig. 3a has signal peaks due to χ_{c0} and χ_{c2} charmonium states. We fit the mass plots with two Breit-Wigners plus polynomial background function and obtain 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 use similar cuts as used in $\psi(2S) \to \gamma\pi^+\pi^-$ except that we now require 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 with a possible signal of $f_2^{'}(1525)$ (Fig. 5). We fit the data using an 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 71.9 ± 14.4 events underneath the $f_J(1710)$ signal and a branching fraction:

$$B(\psi(2S) \to \gamma f_J(1710) \to \gamma K^+K^-) \\ = (5.8 \pm 2.0 \pm 1.0) \times 10^{-5}$$

The systematical error, which is the second error in the expression, includes uncertainties from varying the cuts, the error on the total number of $\psi(2S)$'s 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 begin 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 $|M_{\pi^+\pi^-} - M_{K_S^0}| < 20\ MeV$. At least one of the combinations should pass a four-constraint fit with χ^2 probability larger than 0.01. If there is more than one combination, we select the combination with the 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 6.8 ± 3.1 events or an upper limit of 10.8 events at 90% confidential level and an upper limit of the branching fraction:

$$B(\psi(2S) \to \gamma f_J(1710) \to \gamma K_S^0 K_S^0) \\ = (2.2 \pm 1.0 \pm 1.2) \times 10^{-5}$$

or

$$< 4.2 \times 10^{-5} \quad (90\%\ C.L.)$$

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

Event selection from this channel is more difficult than selecting the $\gamma\pi^0\pi^0$ final state because the η decay into two photons has a relatively large opening angle so there is less help provided by 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 $M_{\gamma\gamma} = M_\eta \pm 70\ MeV$. In the region $M_{\eta\eta} < 3\ GeV$,no evidence for $\eta\eta$ final states are observed. In region where $M_{\eta\eta} > 3\ GeV$ 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:

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

$$B(\chi_{c2} \to \eta\eta) < 1.28 \times 10^{-3} \quad (90\%\ C.L.)$$

Flavor SU(3) symmetry predicts 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 study, we determined:

$$\frac{B(\chi_{c0} \to \eta\eta)}{B(\chi_{c0} \to \pi^0\pi^0)} = 0.73 \pm 0.31 \pm 0.23$$

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

VI. SUMMARY

In this paper we report the first measurement of the $\psi(2S) \to \gamma f_2(1270)$ and $\psi(2S) \to \gamma f_J(1710) \to \gamma K\overline{K}$ branching fractions in the $\psi(2S) \to \gamma\pi^+\pi^-$, $\gamma\pi^0\pi^0$, γK^+K^-, $\gamma K^0_S K^0_S$ and $\gamma\eta\eta$ final states. The results are consistent with the "15%" theoretical prediction.

The glueball candidate $f_J(1710)$ has been observed in radiative decay of J/ψ into $K\overline{K}$, but not in the reaction of $K^-p \to KK\Lambda$. The later result exclude $f_J(1710)$ as an $s\overline{s}$ state. In this paper, we report a clear signal of $f_J(1710)$ in $\psi(2S)$ radiative decay into K^+K^- final states. This is expected as $\psi(2S)$ is differed from J/ψ only by the radial wavefunction.

In addition, we also report the first measurement 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 SU(3) flavor symmetry.

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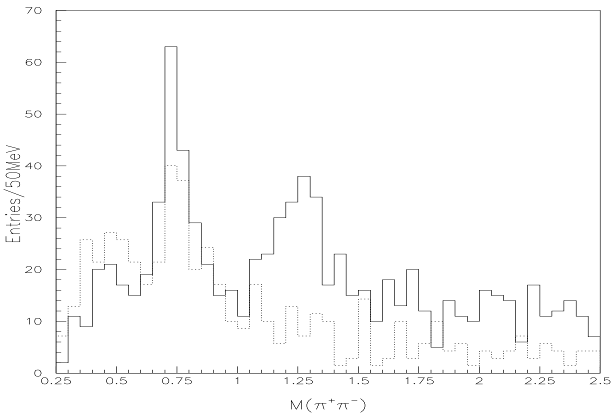

FIG. 1. $M_{\pi^+\pi^-}$ from $\psi(2s)$ data in the solid-line histogram and luminosity normalized τ data in the dash-line histogram

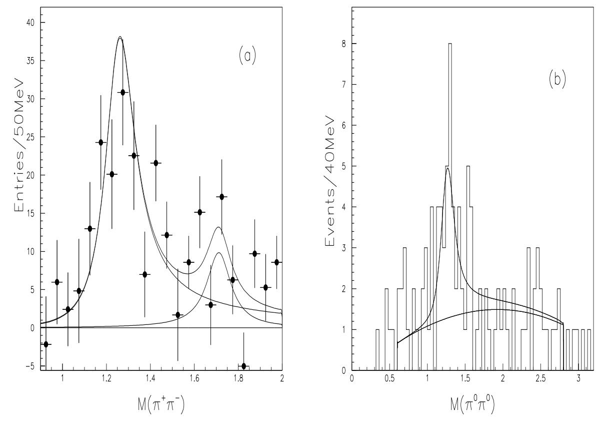

FIG. 2. (a): $M_{\pi^+\pi^-}$ fitting result. The data point is difference of the two histograms in Fig. 1 (b): $M_{\pi^0\pi^0}$

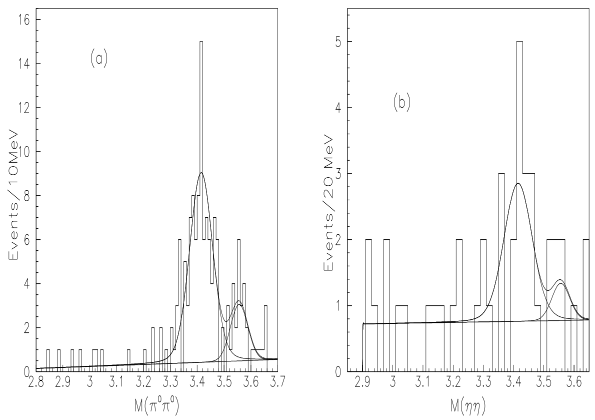

FIG. 3. Invariant mass of (a) $\pi^0\pi^0$ and (b) $\eta\eta$

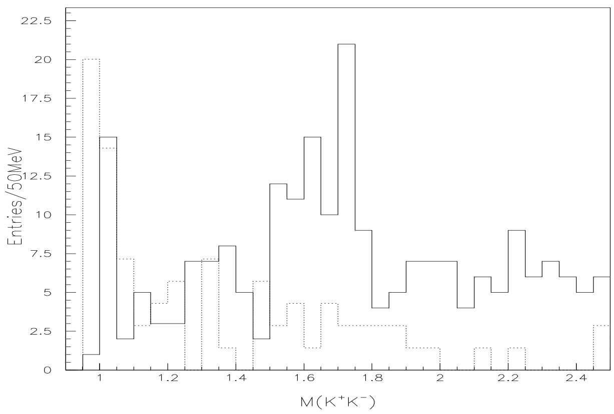

FIG. 4. $M_{K^+K^-}$ from $\psi(2s)$ data in the solid-line histogram and luminosity normalized τ data in the dash-line histogram

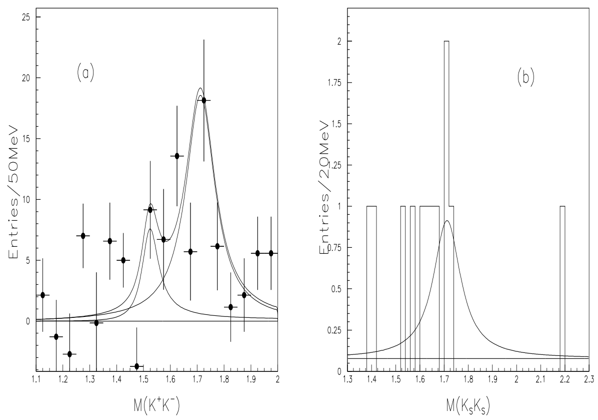

FIG. 5. Invariant mass of (a) K^+K^- and (b) $K_S^0K_S^0$. The data point in (a) is the difference of the two histograms in Fig. 4