Ψ(2S) Hadronic Decays into ω and ϕ and Strong DOZI Violation

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Abstract

We presented the first measurements of the branching ratios of Ψ(2S) decays into $\omega\pi^+\pi^-$, $\phi\pi^+\pi^-$, ωK^+K^-, ϕK^+K^-, $\omega p\bar{p}$, $\phi p\bar{p}$ and ϕf_0, $\pi^0\pi^+\pi^-p\bar{p}$, $\eta\pi^+\pi^-p\bar{p}$ and $\eta p\bar{p}$, and observed the strong OZI and DOZI violation w.r.t. the naive $\omega \sim \phi$ mixing model in $\Psi(2S)$ decays, the violation factors $R = \frac{Br(\phi X)}{Br(\omega X)}$ to the model predictions are of about two order of magnitude for Ψ(2S) decays into $\omega\pi^+\pi^-$, $\phi\pi^+\pi^-$, ωK^+K^-, ϕK^+K^-, while for $\omega p\bar{p}$, $\phi p\bar{p}$, the violation is not serious, but the results coincide with the pQCD and large N_C QCD predictions. The ratios of $\Psi(2S)$ to J/ψ hadronic decay branching fractions of $\omega\pi^+\pi^-$, ϕK^+K^-, $\omega p\bar{p}$ and $\eta p\bar{p}$ are smaller than the perturbative QCD predictions at least by a factor of 2, while for ωK^+K^-, $\phi\pi^+\pi^-$, ϕf_0, $\phi p\bar{p}$, $\eta\pi^+\pi^-p\bar{p}$ and $\pi^0\pi^+\pi^-p\bar{p}$, the ratios are consistent with the perturbative QCD predictions within errors.

1 Introduction

Charmonium decays provide a unique system for the study of hadron dynamics and light quark spectroscopy. Since the discovery of charmonia, fruitful achievement has been obtained, especially the hadronic and radiative decays of J/ψ. And we have got much more knowledge about the J/ψ decays, while in constrast to J/ψ decays, we knew much less about the $\Psi(2S)$ decays [1] because of lower statistic data. With the available date sample of $(3.79 \pm 0.31) \cdot 10^6$ $\Psi(2S)$ [2] collected with the BES detector at Beijing Electron Positron Collider (BEPC) storage ring at a center-mass of energy $\sqrt{s} = M_{\Psi(2S)}$, in this paper, we present the study of some $\Psi(2S)$ hadronic decay modes.

Out of the charmonium decays, there exists a mysterious and longstanding $\Psi(2S) \to \rho\pi$ puzzle of J/ψ and $\Psi(2S)$ decays [3], first revealed by Mark-II Collaboration. The charmonia are nonrelativistic bound states of a charm quark and its antiquark. Their decays into light hadrons are thought to be dominated by the annihilation of the $c\bar{c}$ pair into three gluons, or via a virtual photon. In such simple case, the partial width for decays into any specific final hadronic state h consisting of light hadrons is therefore proportional to the wave function $\Psi(0)$ at the origin. Based on the similarity between the $\Psi(2S)$ and J/ψ wave functions and the slow running of the strong coupling constant α_s, the perturbative QCD predicts the ratios of the decay width of $\Psi(2S)$ decays into hadrons to that of J/ψ decays into hadrons can be expressed as: [4]

$$Q_h = \frac{Br(\Psi(2S) \to h)}{Br(J/\psi \to h)} = \frac{Br(\Psi(2S) \to e^+e^-)}{Br(J/\psi \to e^+e^-)} = (14.7 \pm 2.3)\%$$

which is known as "15%" rule, where the leptonic branching fractions are taken from the PDG tables [1]. The observed results[3] of $\rho\pi$ and $K^{\star}\bar{K}$ with $Q_{\rho\pi} < 0.6\%$ and $Q_{K^{*}K} < 2\%$ at $CL = 90\%$ significantly violate the theoretical predictions, BES confirms the results of $Q_{\rho\pi} < 0.23\%$, $Q_{K^{*}K} < 0.64\%$ and $Q_{K^{*0}\bar{K}^{0}} = (1.7 \pm 0.6)\%$ at higher precision [5] and reveals new dramatic violation of "15%" rule in vector plus tensor decay modes[6]. Various theoretical models[7] have been put forward to explain the puzzle, but none of them is satisfactory.

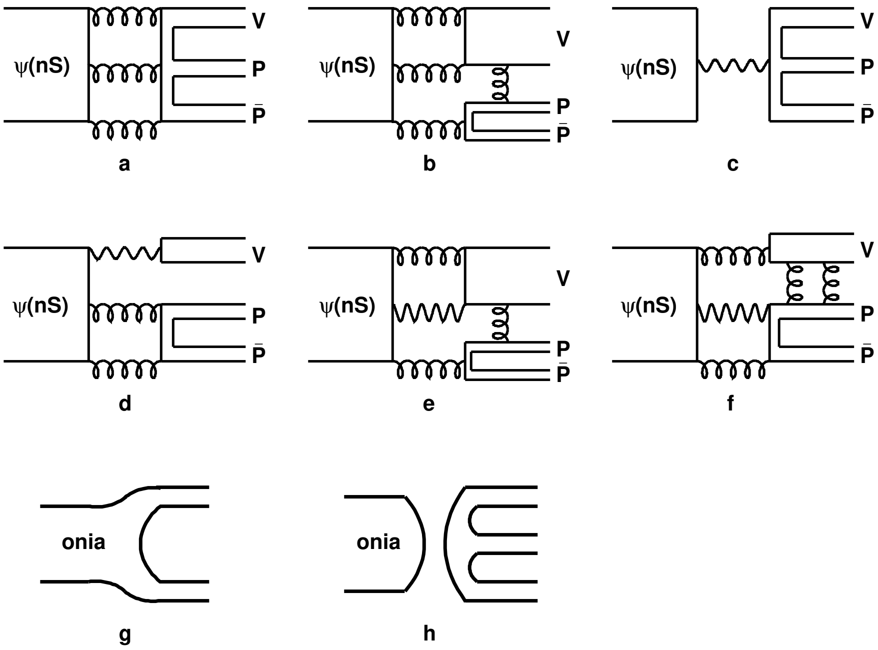

Figure 1: The lowest order digrams of charmonium three body decays. Charmonium decays into hadrons via (a) ggg, (b) ggg but DOZI suppressed, (c-f) electromagnetic decays into hadrons with (c, d) SOZI and (e, f) DOZI suppressed. Where V stands for vector mesons, P for pseudoscalar mesons.

In recent years, the abundant ϕ meson production in nucleon-antinucleon and meson-nucleon annihilation were observed in experiments [8]. Of special interest are the processes violating the Okubo-Zweg-Iizuka (OZI) rule [9], Two different approaches have been used to interpret such strong violation of the OZI rule, one assumes the existence of the large intrinsic strange components $s\bar{s}$ in nucleons [10] , the other is based on the $\omega \sim \phi$ mixing and the high order processes [11]. The tree level expectations of the relative ϕ and ω production rates based on the deviation of the $\omega \sim \phi$ mixing angle from the so-called ideal one are of order $(\theta_i - \theta)^2 \sim (1 - 4.2) \cdot 10^{-3}$ [1]. Experiments observe both conversation [12] and violation of the OZI rule [8].

Of course, the OZI rule is evidently not absolute, it is a good approximation for a large number of strong interaction processes. Attempts have been made to understand the origin of the OZI rule within the framework of $N_C = 3$ QCD [14], it has been shown that the OZI rule should work well for heavy flavors [4]. But it is established that the OZI rule emerges as a rigorous consequence of the application of the large N_C limit to QCD. It has been proved that, in the large N_C limit, the transition amplitude of the connected quark line diagram corresponding to Fig. 1g is $N_C^{-1/2}$ whereas it is $N_C^{-3/2}$ in the case of the disconnected quark line diagram of Fig. 1h. From another aspect, the large N_C estimates clearly tell us that the relative decay widths of the OZI forbidden processes and the allowed ones are about N_C^{-2} in large N_C limit. The OZI rule is rigorous in the $N_C \to \infty$ limit, but we have no way to estimate the degree of accuracy of the OZI rule for finite $N_C = 3$, the violation of the OZI rule may occur.

The charmonium decays into vector-pseudoscalar-pseudoscalar (VPP) final states are expected to proceed mainly by two mechanisms through the sequential process described in Fig. 1(a-f): strong decays via $c\bar{c}$ annihilation into three gluons (Fig. 1a), then they decay into hadrons; and the substantial contributions from the electromagnetic annihilation through one virtual photon (Fig. 1c) which then decays into hadrons. The electromagnetic contributions to the decays are important since the strong decays are OZI suppressed. Doubly OZI suppressed amplitudes (e.g. Fig. 1b, e, f) may also contribute to the decays rates for the interference between the DOZI and the large SOZI processes.

Foutunately, the perturbative QCD has been proved to be applicable for the heavy quarkonia [4]. Therefore for charmonium decay into light flavor hadrons, a rough estimate gave [13]:

$$\frac{\Gamma(\psi \to \phi\pi^+\pi^-)}{\Gamma(\psi \to \omega\pi^+\pi^-)} \sim 0.14$$

with $\alpha_s(m_\phi^2) = 0.55$ and neglecting the small phase-space difference and the wave function discrepancy in the binding of ω and ϕ, and $\Gamma(\psi \to \phi K^+K^-)$ and $\Gamma(\psi \to \omega K^+K^-)$ are comparable. The similar results can be drawn for $\Psi(2S)$ decays, but it gave:

$$\frac{\Gamma(\psi' \to \phi\pi^+\pi^-)}{\Gamma(\psi' \to \omega\pi^+\pi^-)} > \frac{\Gamma(\psi \to \phi\pi^+\pi^-)}{\Gamma(\psi \to \omega\pi^+\pi^-)}$$

since the small difference of α_s at $\sqrt{s} = m_\psi$ and $m_{\psi'}$ and the wave function of ψ and ψ' at the origin.

We present herein the first measurements of the Ψ(2S) decays into $\omega\pi^+\pi^-$, $\phi\pi^+\pi^-$, ωK^+K^-, ϕK^+K^-, $\omega p\bar{p}$, $\phi p\bar{p}$ and meanwhile ϕf_0, $\pi^0\pi^+\pi^-p\bar{p}$, $\eta\pi^+\pi^-p\bar{p}$ and $\eta p\bar{p}$. The data consists of $(3.79\pm0.31)\cdot10^6$ $\Psi(2S)$ taken with the BES detector at BEPC. After the description of the BES detector in Sec. II, Sec. III presents the general event selection criteria, Sec. III deals with the analyses of the specific decay channels, finally we summarize the results in the last section.

2 The BES Detector

The BEijing Spectrometer detector, BES, is a large solid-angle cylindrical magnetic spectrometer that is described in detail elsewhere [15]. A four-layer central drift chamber (CDC) which is coaxial with the beampipe provides trigger information. Outside the CDC, the 40-layer main drift chamber (MDC) provides tracking and energy-loss (dE/dX) information on charged tracks over 85% of the total solid angle. The momentum resolution for charged tracks is $\sigma_p/p = 0.017\sqrt{1+p^2}$ (p in GeV/c). An array of 48 scintilation counters surrounding the MDC prodives measurements of the time of flight (TOF) of the charged tracks with a resolution of $\sim 450ps$ for hadrons. Outside the TOF system, a 12 radiation length lead-gas barrel showre counter (BSC), operating in self-quenching streamer mode, measures the energies of electrons and photons over 80% of the total solid angle. The energy resolution is $\sigma_E/E = 0.22/\sqrt{E}$ (E in GeV), and the spatial resolution $\sigma_\phi = 4.5$ mrad and $\sigma_\theta = 12$ mrad. Surrounding the BSC locates a solenoidal magnet that prodives a 0.4 Tesla magnetic field in the central tracking region of the detector. There are double layers of proportional chambers intrumented the magnet flux return and are used to identify muons (MUID) of momentum greater than 0.5 GeV/c. Endcap time of flight and shower counters extend coverage to the forward and backward regions.

3 Event Selection

3.1 Method

In order to get better particle separation, combine kinematic fit and dE/dX information for particle identification. For different particle assignments, the smallest χ square:

$$\chi^2 = \chi^2_{fit} + \sum_i (\chi^2_{s_i dE/dX}) \tag{1}$$

is selected as the best one, where χ^2_{fit} is the χ square for the kinematic fit , and

$$\chi_{s_i dE/dX} = \frac{(dE/dX)^{meas} - (dE/dX)^{th}_i}{\sigma_i^{(dE/dX)}}$$

is the measured dE/dX pulse height $(dE/dX)^{meas}$ deviation of the i^{th} particle from the theoretical expectation $(dE/dX)^{th}_i$ as a certain particle hypothesis, $\sigma_i^{(dE/dX)}$ is the resolution of dE/dX pulse height, and summation over all final charged particles with good helix reconstructed tracks.

3.2 General Cut Criteria

The decay channels to be investigated are $\Psi(2S)$ decays into $(\omega, \phi) + (\pi^+\pi^-, K^+K^-, p\bar{p})$, then ω into $\pi^+\pi^-\pi^0$ then π^0 into 2γ and ϕ into K^+K^-, at the same time, the decays of $\Psi(2S) \to \pi^+\pi^-\pi^0 p\bar{p}$ and $\eta\pi^+\pi^- p\bar{p}$ with (π^0, η) decays to $\gamma\gamma$, $\Psi(2S) \to \phi f_0$ with $\phi \to K^+K^-$ and $f_0 \to \pi^+\pi^-$, and $\Psi(2S) \to \eta p\bar{p}$ with $\eta \to \pi^+\pi^-\pi^0$ then π^0 into 2γ are also analyzed. The final states are 4-prongs for the events involving ϕ and 4-prongs plus at least 2γ candidates for those involving ω, η or π^0. The branching ratios of the intermediate states used here are taken from PDG [1].

Candidate events are required to have four charged tracks of good reconstructed helix track with zero total net charge and at least two photon candidates detected in Barrel Shower Counter(BSC) for those involving ω, η, π^0. Each track is required to lie in the polar angle $|cos\theta| < 0.8$, the neutral clusters not hitting the central ribbon regions, and the event vertex in the regions $V_{xy} = \sqrt{V_x^2 + V_y^2} < 1.5$ cm and $|V_z| < 15$ cm, any identified charged track is required to be in the 3σ separation of dE/dX, i.e, $|\chi_s| < 3$. Photon candidates are required to hit Barrel Shower Counter (BSC) at least 2 layers and not come from the charged particles, and the energy E_γ^{fit} of photon after kinematic fit is required to be greater than 60 MeV or 50 MeV. Any event with identified electrons or muons is discarded, and J/ψ background is rejected if the recoil mass and the invariant mass of any oppositely-charged particle pair lies in $(3.05, 3.15)$ GeV. In order to get better ω mass resolution, an extra contraint (5-Contraints) with two photons forming a resonance π^0 is applied into the kinematic fit, only 4-C fit is done for the processes without photons. The χ^2-probability for kinematic fit $CL(fit) = prob(\chi^2_{fit}, ndf_{fit})$ and that of dE/dX for all charged tracks $CL(dE/dX) = prob(\sum_i \chi^2_{s_i dE/dX}, ndf_{dE/dX})$ are both required to be greater than 1%, where ndf's are the corresponding number of degree of freedom for kinematic fit and dE/dX. The total χ^2 probability of kinematic fit plus dE/dX for the signals is required to be greater than that for the background to reject the backgrounds.

3.3 $\Psi(2S) \to \omega\pi^+\pi^-$

The candidate events with the topology $\gamma\gamma\pi^+\pi^-\pi^+\pi^-$ are selected. The events satisfying the general cuts are kinematically $5C - 2\gamma$ fitted with all pairs of photon candidates forming a resonance π^0, the pair with the highest probability of the kinematic fit are selected and it is also required to be greater than 1% and the probability of dE/dX of all charged tracks is larger than 1%. The background ωK^+K^- is rejected if the events with the probability of 5-C kinematic fit and that of dE/dX greater than 1%, and the total χ^2 probability of 5-C kinematic fit plus dE/dX greater than that of $\omega\pi^+\pi^-$. The enengy of photon after fit is required $E_\gamma^{fit} > 60$MeV.

Fig. 2 diagrams the unbinned Breit-Wigner fit for $\pi^+\pi^-\pi^0$ mass , An obvious ω signal over the combinational background can be seen at (0.7831 ± 0.002) GeV, 79.3 ± 10.2 events are observed, and the fitted results will be listed in Table 1. The fitted ω mass well accords with the PDG value [1]. The acceptance is 5.34% determined from Monte Carlo. The determined branching ratio here is:

$$Br(\Psi(2S) \to \omega\pi^+\pi^-) = (4.47 \pm 0.57 \pm 0.54) \cdot 10^{-4}.$$

the first error is statistic one, and the second is systematic.

3.4 $\Psi(2S) \to \phi\pi^+\pi^-$

The decay is observed in the final state topology $\pi^+\pi^-K^+K^-$. As describe in Sec. 3.1, the kinematic fit is combined with the dE/dX information to get better particle separation. The events with the smallest total $\chi^2 = \chi^2_{4C-fit} + \sum_i(\chi^2_{s_i dE/dX})$ of fit and dE/dX for different π/k hypotheses are selected, and also required the 4-C fit probability and all charged particle dE/dX probabilty are above 1%. To reject background, the combined probability of 4-C fit plus dE/dX should be greater than those of $\Psi(2S)$ decays into $K^+K^-K^+K^-, \pi^+\pi^-\pi^+\pi^-$.

The unbinned Breit-Wigner fit for the ϕ signals is shown in Fig: 3, 57.4 ± 7.2 events are observed, the fitted ϕ mass is (1.0185 ± 0.001) GeV, precisely consistent with the PDG value

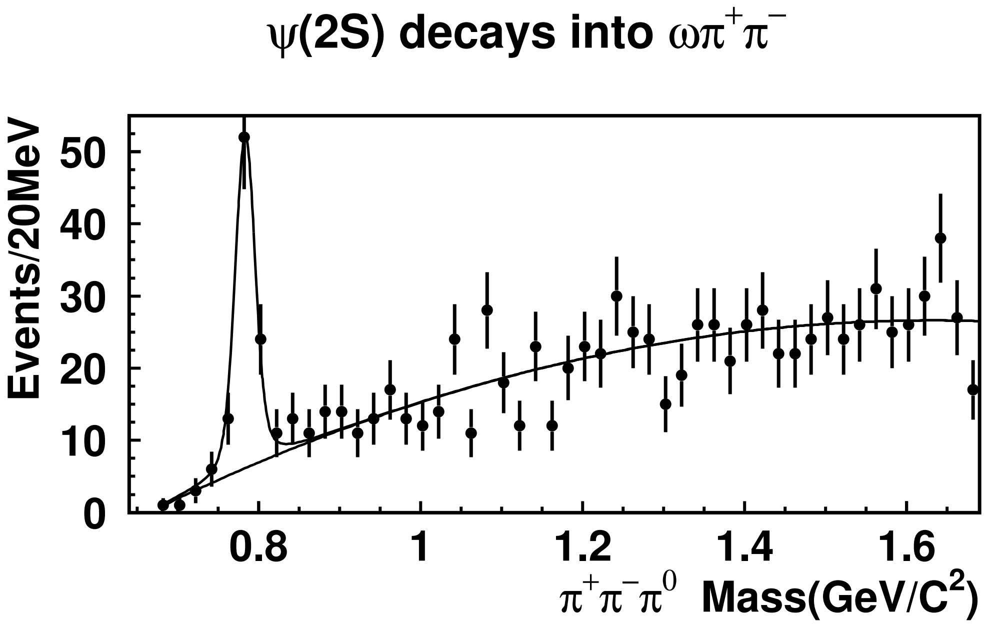

Figure 2: Breit-Wigner fit for the mass of $\pi^+\pi^-\pi^0$ (4 entries per event) in $\Psi(2S) \to \omega\pi^+\pi^-$. The curve is the result of a fit to a Breit-Wigner convoluted with a Gaussian plus a second order polynomial.

[1]. MC gives the acceptance is 17.61%. The branching ratio is determined as:

$$Br(\Psi(2S) \to \phi\pi^+\pi^-) = (1.76 \pm 0.22 \pm 0.24) \cdot 10^{-4}.$$

the first error is statistic one, and the second is systematic.

3.5 $\Psi(2S) \to \phi f_0(980)$

As a controversial candidate of exotic states, scalar meson $f_0(980)$ with $J^{PC} = 0^{++}$, is sepecially intriguing for both theories and experiments [16]. Here the production of $f_0(980)$ in $\Psi(2S)$ decays is also analysed. An extra cut requires the K^+K^- invariant mass lies in region (1.0,1.04) GeV besides the cuts listed in Sec. 3.4. The recoil $\pi^+\pi^-$ mass against ϕ is dipicted in Fig. 4. The $f_0(980)$ decay width used here is $\Gamma_{f_0} = 50MeV$ [18]. The Breit-Wigner fit gives 20.3 ± 5.2 $\phi f_0(980)$ events observed, the fitted f_0 mass is (0.9834 ± 0.008) GeV, in good accordance with the PDG value [1]. The acceptance is 21.27% from MC. The branching fraction is:

$$Br(\Psi(2S) \to \phi f_0) = (6.57 \pm 1.68 \pm 0.77) \cdot 10^{-5}.$$

the first error is statistic one, and the second is systematic.

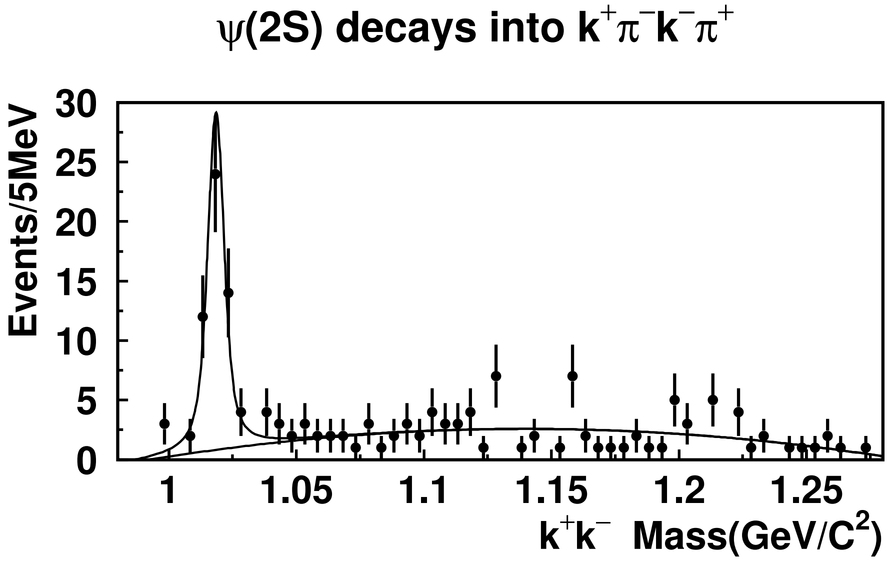

Figure 3: Breit-Wigner fit for K^+K^- masses in $\Psi(2S) \to \phi\pi^+\pi^-$. The curve is the result of a fit to a Breit-Wigner convoluted with a Gaussian plus a second order polynomial.

3.6 $\Psi(2S) \to \omega K^+K^-$

The final states are $\gamma\gamma\pi^+\pi^-K^+K^-$. After general cuts, 5C-2γ kinematic fit is done with all pairs of photon candidates forming a resonance π^0 and loop over different π/k hypotheses for all charged tracks, the kinematic fit is combined with dE/dX information, events with the lowest total $\chi^2 = \chi^2_{5C-fit} + \sum_i(\chi^2_{s_i dE/dX})$ are selected, and also the probability of 5-C fit and that of dE/dX are required to be greater than 1%. The fitted energy E_γ^{fit} of photon is required to be above 60 MeV. To exclude background $\omega\pi^+\pi^-$, $\omega\pi^+\pi^-$ is identified if the probability of 5-C fit and that of dE/dX of all charged particle are greater than 1%, and also the total χ^2 probability of 5-C fit plus dE/dX is required to be greater than that of ωK^+K^-.

Diagrammatically, Fig. 5 represents the $\pi^+\pi^-\pi^0$ invariant mass. The fit gives 16.2 ± 5.5 events observed, the fitted ω mass is (0.7823 ± 0.006) GeV, and coincide with the PDG data with a bit larger error [1] .

The acceptance determined from MC is 3.86%. The measured branching ratio is:

$$Br(\Psi(2S) \to \omega K^+K^-) = (1.26 \pm 0.43 \pm 0.39) \cdot 10^{-4}.$$

the first error is statistic one, and the second is systematic.

3.7 $\Psi(2S) \to \phi K^+K^-$

The final state topology is $K^+K^-K^+K^-$, 4-C Kinematic fit is done for the events passing the above general cuts (see Sec. 3.2), the probability of 4-C fit and that of dE/dX for the

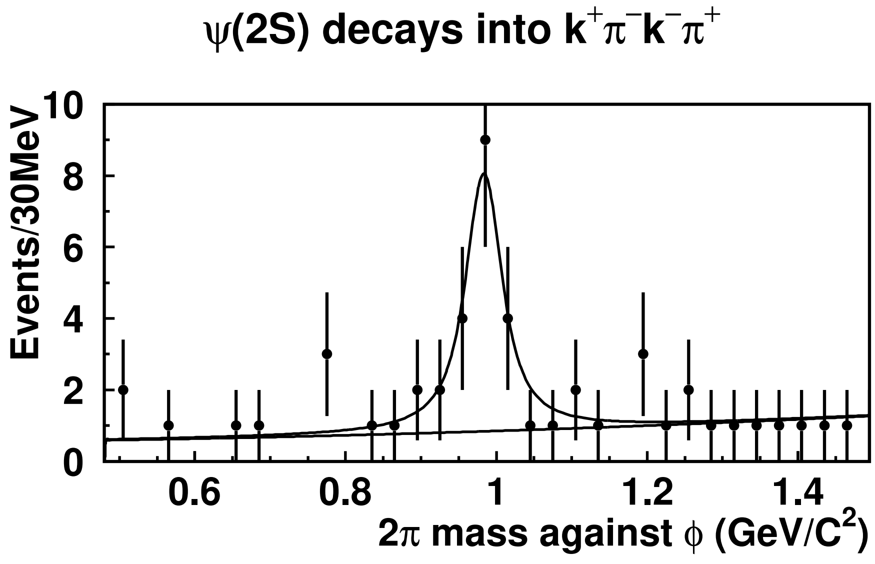

Figure 4: $\Psi(2S) \to \phi f_0$, the unbinned Breit-Wigner fit for $\pi^+\pi^-$ invariant mass against ϕ. The curve is the result of a fit to a Breit-Wigner convoluted with a Gaussian plus a second order polynomial.

selected events are larger than 1%. To remove the backgrounds, the total χ^2 probability of 4-C fit plus dE/dX should be greater than those of $\Psi(2S) \to \pi^+\pi^-K^+K^-, \pi^+\pi^-\pi^+\pi^-$.

Fig. 6 shows the K^+K^- invariant mass distribution. 18.1 ± 5.3 events are observed from the unbinned Breit-Wigner fit, the fitted ϕ mass is (1.0189 ± 0.002) GeV, precisely consitent with the PDG value [1]. MC determines the acceptance is 15.94%. The decay branching fraction is:

$$Br(\Psi(2S) \to \phi K^+K^-) = (6.10 \pm 1.79 \pm 1.51) \cdot 10^{-5}.$$

the first error is statistic one, and the second is systematic.

3.8 $\Psi(2S) \to \omega p\bar{p}, \eta p\bar{p}$

The two processes have the same event topology $\gamma\gamma\pi^+\pi^-p\bar{p}$ with (ω, η) decays into $\pi^+\pi^-\pi^0$ then π^0 into $\gamma\gamma$. The events passing the general cuts (see Sec. 3.2) are 5-C fitted with all pairs of photon candidates resonating a π^0 and loop over all possible π/p assignments, the kinematic fit and dE/dX are combined. The events with the lowest value of total χ square: $\chi^2 = \chi^2_{5C-fit} + \sum_i(\chi^2_{s_i dE/dX})$ are selected, and also required to pass the probability cuts ($\geq$ 1%) for 5-C fit and for the dE/dX (see Sec. 3.2). To exclude the backgrounds, the total χ^2 probability of 5-C fit plus dE/dX should be greater than those of $\Psi(2S) \to \omega K^+K^-, \omega\pi^+\pi^-$. The fitted energies of photons are greater than 60 MeV. Analysis indicates there exists very good π/p separation at BES.

The unbinned Breit-Wigner fit result is represented in Fig. 7. 11.0 ± 4.3 events are observed, the fitted ω mass is (0.779 ± 0.006) GeV which is consistent with the PDG value

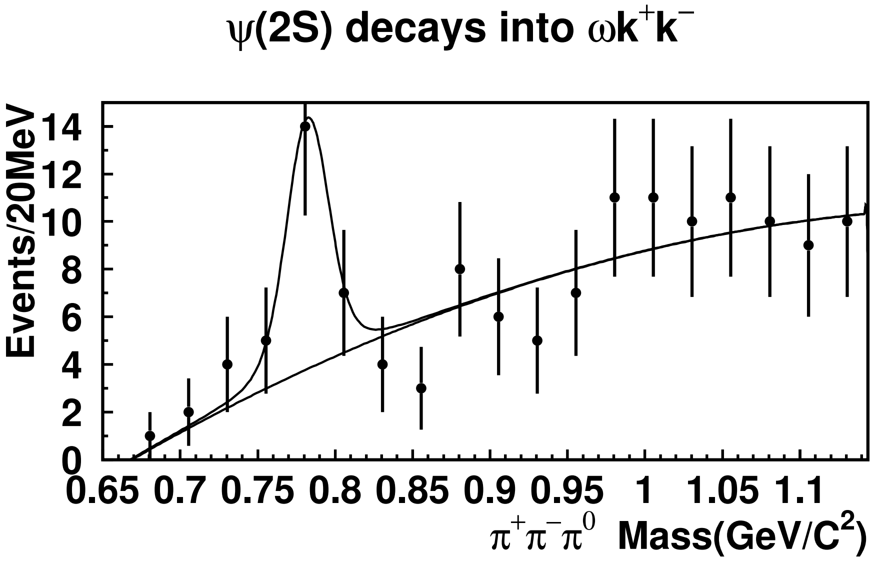

Figure 5: $\Psi(2S) \to \omega K^+K^-$, The unbinned Breit-Wigner fit for $\pi^+\pi^-\pi^0$ invariant mass. The curve is the result of a fit to a Breit-Wigner convoluted with a Gaussian plus a second order polynomial.

within a lot larger error. MC gives 5.52% acceptance. The branching ratio is determined as:

$$Br(\Psi(2S) \to \omega p\bar{p}) = (6.00 \pm 2.34 \pm 1.41) \cdot 10^{-5}.$$

the first error is statistic one, and the second is systematic.

Meanwhile, 3 events of η signals are observed with clear signals and the acceptance $\epsilon = 4.13\%$ and $\sigma_{m_\eta} = 7.0$ MeV, and the branching ratio is:

$$Br(\Psi(2S) \to \eta p\bar{p}) = (8.36 \pm 4.8 \pm 4.8) \times 10^{-5}.$$

The errors are statistical and systematic respectively.

3.8.1 $\Psi(2S) \to \pi^0\pi^+\pi^-p\bar{p}, \eta\pi^+\pi^-p\bar{p}$

These two channels with (π^0, η) decays into $\gamma\gamma$ have the same final states as Sec. 3.8. The method is same as Sec. 3.8, here only 4-C fit is done. The fitted energies of photons is required to be larger than 50 MeV. The prominent (π^0, η) signals can be seen from Fig. 8. The unbinned Breit-Wigner fit shows 112.4 ± 11.0 and 35.0 ± 9.2 events are observed for $\Psi(2S)$ decays into $\pi^0\pi^+\pi^-p\bar{p}, \eta\pi^+\pi^-p\bar{p}$ respectively. The fitted resonance masses are $m_{\pi^0} = (0.1353 \pm 0.002)$ GeV and $m_\eta = (0.5364 \pm 0.006)$ GeV, π^0 mass agrees well with the PDG value, while η mass with a bit larger error. The acceptance determined from MC is 7.80% for $\Psi(2S) \to \pi^0\pi^+\pi^-p\bar{p}$ and 9.14% for $\Psi(2S) \to \eta\pi^+\pi^-p\bar{p}$. The branching fractions

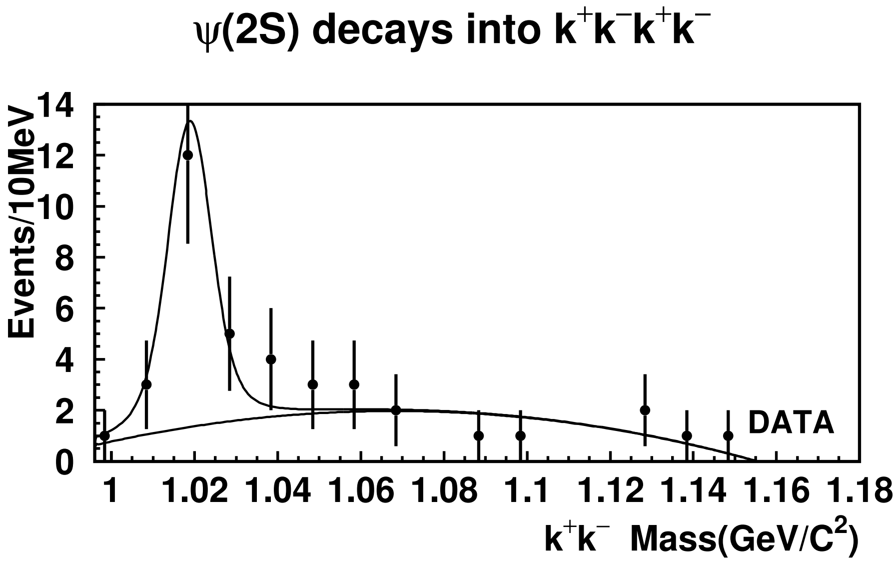

Figure 6: $\Psi(2S) \to \phi K^+K^-$, the unbinned Breit-Wigner fit for K^+K^- invariant mass (4 entries per event). The curve is the result of a fit to a Breit-Wigner convoluted with a Gaussian plus a second order polynomial.

of these two channels are:

$$Br(\Psi(2S) \to \pi^0\pi^+\pi^- p\bar{p}) = (3.85 \pm 0.37 \pm 0.56) \cdot 10^{-4}.$$

$$Br(\Psi(2S) \to \eta\pi^+\pi^- p\bar{p}) = (2.58 \pm 0.67 \pm 0.75) \cdot 10^{-4}.$$

the first errors are statistical ones, and the second ones are systematic.

3.9 $\Psi(2S) \to \phi p\bar{p}$

The concrete method is same as $\Psi(2S) \to \phi\pi^+\pi^-$ (See Sec. 3.4). The kinematic fit (4-C) is combined with the dE/dX information to get better particle separation, the events with the smallest total $\chi^2 = \chi^2_{4C-fit} + \sum_i(\chi^2_{s_i dE/dX})$ are selected, and are required that the probability of 4-C fit and that of the dE/dX are greater than 1%, the total χ^2 probablity of 4-C fit plus dE/dX must be greater than those of $K^+K^-K^+K^-, \pi^+\pi^-K^+K^-$ to exclude these backgrounds.

From Fig. 9, only few events with $m_{K^+K^-} = 1.01459, 1.00636, 0.999595, 1.04043, 1.092$ GeV at low mass region are observed. The acceptance is 18.69% from MC, the branching ratio and the upper limit are:

$$Br(\Psi(2S) \to \phi p\bar{p}) = (0.57 \pm 0.28 \pm 0.13) \cdot 10^{-5}.$$

the first error is statistic one, and the second is systematic.

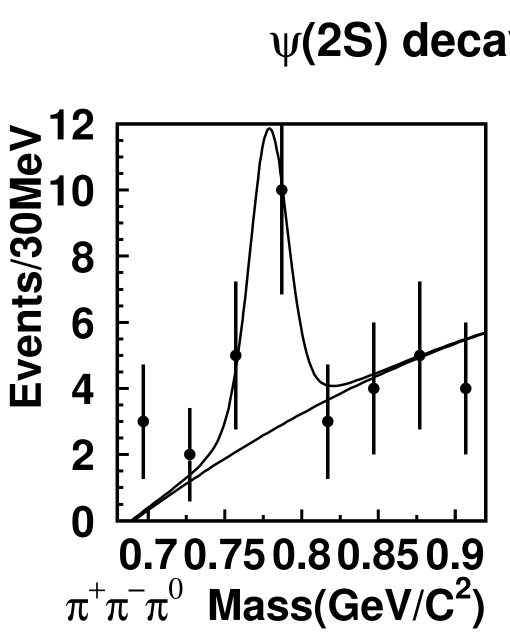

Figure 7: $\Psi(2S) \to \omega p\bar{p}$, The unbinned Breit-Wigner fit for $\pi^+\pi^-\pi^0$ invariant mass. The curve is the result of a fit to a Breit-Wigner convoluted with a Gaussian plus a second order polynomial.

4 The Systematic Errors

MC study indicates the background are negligible after the general cuts and the specific cuts for each decay channel. The systematic errors mainly come from the following sources: 1). the event selection criteria; 2). the errors of the acceptance and the mass resolution from MC simulation; 3). the errors of the total number of $\Psi(2S)$; 4) the errors of ϕ, ω, η and π^0 decay branching ratios used in our calculations. Let the cuts vary a standard deviation from the determined value, namely, the probability cuts shift from 1% to 4%; the fitted energy of photon varies from 60 MeV$\rightleftharpoons$ 50 MeV; mass resolution shifts around 10% from the MC determined values; polar angle $|cos\theta|$ cut shifts from 0.8 to 0.75; the recoil mass m_{recoil} to reject J/ψ background shifts from $m_{J/\psi} \in (3.05, 3.15)$ to $m_{J/\psi} \in (3.00, 3.20)$; the dE/dX particle separation within 3σ for each charged track varies from $|\chi_s| < 3$ to $|\chi_s| < 3.5$ for each charged track. We obtain the systematic errors for the all decay channels and they will listed in Table 1.

5 Results and Discussions

The results are listed in Table 1. From the table, we can see that the fitted masses of resonances for the processes $\Psi(2S) \to \omega\pi^+\pi^-$, ωK^+K^-, $\phi\pi^+\pi^-$, ϕK^+K^-, $\pi^0\pi^+\pi^-p\bar{p}$ and ϕf_0 accords very well with the PDG values[1], and those for $\omega p\bar{p}$ and $\eta\pi^+\pi^-p\bar{p}$ are also

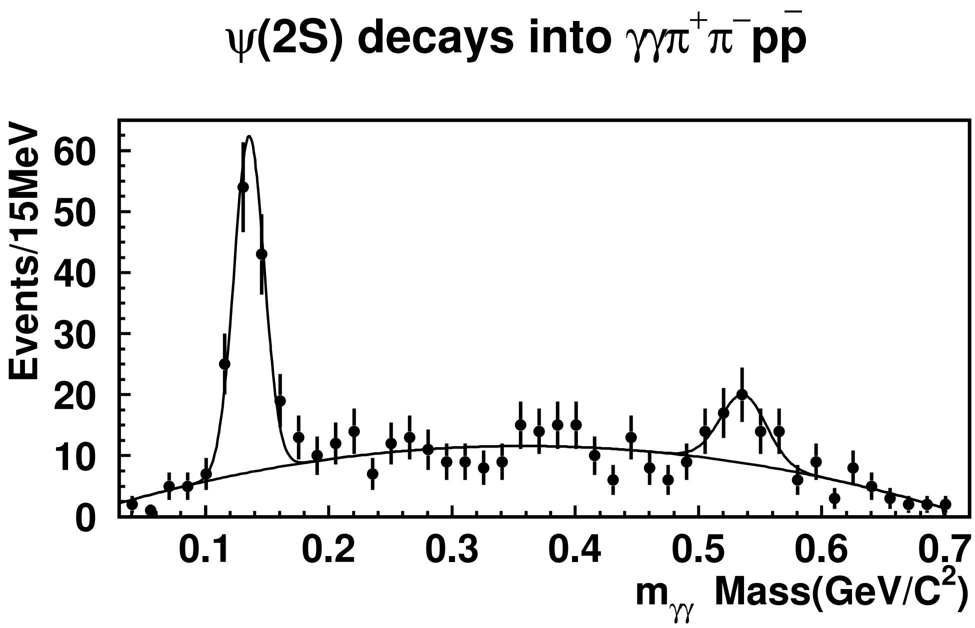

Figure 8: $\Psi(2S) \to (\pi^0, \eta)\pi^+\pi^- p\bar{p}$, the unbinned Breit-Wigner fit for $\gamma\gamma$ invariant mass. The curve is the result of a fit to a Breit-Wigner convoluted with a Gaussian plus a second order polynomial.

consistent with the PDG values but within a bit larger errors.

5.1 Tests of the OZI rule

Using these results, we can test the OZI rule and QCD "15%" rule. The ratios of the branching fraction of $\Psi(2S) \to \phi X$ to that of $\Psi(2S) \to \omega X$ are:

$$R_{(\phi X/\omega X)} = \frac{Br(\Psi(2S) \to \phi X)}{Br(\Psi(2S) \to \omega X)}$$

For the above channels involving ω, ϕ production:

$$R_{(\phi\pi^+\pi^-/\omega\pi^+\pi^-)} = \frac{Br(\Psi(2S) \to \phi\pi^+\pi^-)}{Br(\Psi(2S) \to \omega\pi^+\pi^-)} = (39.3 \pm 7.0 \pm 6.0)\%$$

$$R_{(\phi K^+K^-/\omega K^+K^-)} = \frac{Br(\Psi(2S) \to \phi K^+K^-)}{Br(\Psi(2S) \to \omega K^+K^-)} = (48.4 \pm 21.7 \pm 18.4)\%$$

$$R_{(\phi p\bar{p}/\omega p\bar{p})} = \frac{Br(\Psi(2S) \to \phi p\bar{p})}{Br(\Psi(2S) \to \omega p\bar{p})} = (14.5 \pm 9.0 \pm 4.4)\%$$

The results are consistent with the predictions of the perturbative QCD and large N_C QCD.

While for the J/ψ hadronic decays:

$$\frac{Br(J/\psi \to \phi\pi^+\pi^-)}{Br(J/\psi \to \omega\pi^+\pi^-)} = (11.4 \pm 2.4)\%$$

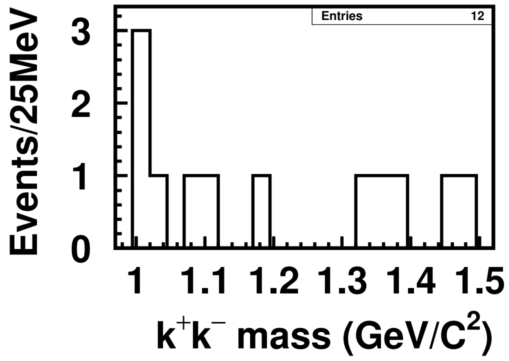

Figure 9: K^+K^- mass distribution in $\Psi(2S) \to \phi p\bar{p}$.

$$\frac{Br(J/\psi \to \phi K^+K^-)}{Br(J/\psi \to \omega K^+K^-)} = (112.2 \pm 40.6)\%$$
$$\frac{Br(J/\psi \to \phi p\bar{p})}{Br(J/\psi \to \omega p\bar{p})} = (3.5 \pm 1.3)\%$$

the ratios of J/ψ and $\Psi(2S)$ hadronic decays are in accordance with the perturbative QCD predictions within errors.

The OZI violation factors, the above ratios to the naive phenomenological $\omega \sim \phi$ mixing model prediction $(1.0 \sim 4.2) \times 10^{-3}$, are:

$$V_{(\phi\pi^+\pi^-/\omega\pi^+\pi^-)} = \frac{0.393}{4.2 \times 10^{-3}} = 93.6 \pm 16.7 \pm 14.3$$
$$V_{(\phi K^+K^-/\omega K^+K^-)} = \frac{0.484}{4.2 \times 10^{-3}} = 115.3 \pm 51.7 \pm 43.8$$
$$V_{(\phi p\bar{p}/\omega p\bar{p})} = \frac{0.145}{4.2 \times 10^{-3}} = 33.9 \pm 21.5 \pm 10.5$$

The strong OZI violation with a factor of about two order of magnitude w.r.t. the naive phenomenological $\omega \sim \phi$ mixing model is observed in $\Psi(2S) \to \phi\pi^+\pi^-$, $\omega\pi^+\pi^-$, ϕK^+K^-, ωK^+K^-, but for $\Psi(2S) \to \omega p\bar{p}, \phi p\bar{p}$, the violation is not serious. Moreover the strong DOZI violation in $\Psi(2S) \to \phi\pi^+\pi^-$, $\omega\pi^+\pi^-$ is also observed with a factor of about two order of magnitude, while for such DOZI process in J/ψ decays, the factor is

$$\frac{Br(J/\psi \to \phi\pi^+\pi^-)}{Br(J/\psi \to \omega\pi^+\pi^-) \times 4.2 \times 10^{-3}} = \frac{8.0 \times 10^{-4}}{7.2 \times 10^{-3} \times 4.2 \times 10^{-3}} = 26.5 \pm 5.4$$

The branching ratios are taken from [1]. Therefore the DOZI violation is much stronger in $\Psi(2S)$ decays than in J/ψ decays.

The comparisons show that the naive phenomenological $\omega \sim \phi$ mixing model poorly describe the processes of $\Psi(2S)$ hadronic decays involving ω and ϕ, the perturbative QCD and large N_C QCD give good description of these processes.

Table 1: Measurements of the $\Psi(2S)$ decay branching ratios. (Note: Γ_{f_0}=50MeV)

$\Psi(2S) \Rightarrow$	ϵ_{acc}	N_{obs}	M_R(GeV)	σ_m(MeV)	Br($\times 10^{-5}$)
$\omega\pi^+\pi^-$	5.34	79.3±10.2	0.7831±0.002	10.3	$44.7 \pm 5.7 \pm 5.4$
ωK^+K^-	3.86	16.2±5.5	0.7823±0.006	12.0	$12.6 \pm 4.3 \pm 3.9$
$\phi\pi^+\pi^-$	17.61	57.4±7.2	1.0185± 0.001	2.1	$17.6 \pm 2.2 \pm 2.4$
ϕK^+K^-	15.94	18.1± 5.3	1.0189±0.002	4.3	$6.10 \pm 1.79 \pm 1.51$
ϕf_0	21.27	20.3±5.2	0.9834±0.008	9.4	$6.57 \pm 1.68 \pm 0.77$
$\omega p\bar{p}$	5.52	11.0±4.3	0.7786±0.006	10.9	$6.00 \pm 2.34 \pm 1.41$
$\phi p\bar{p}$	18.69	3.0±1.7		2.2	$0.86 \pm 0.50 \pm 0.20$
$\pi^+\pi^-\pi^0 p\bar{p}$	7.80	112.4±11.0	0.13531 ± 0.002	12.2	$38.5 \pm 3.7 \pm 5.6$
$\eta\pi^+\pi^- p\bar{p}$	9.14	35.0±9.2	0.5364±0.006	18.7	$25.8 \pm 6.8 \pm 7.3$
$\eta p\bar{p}$	4.13	3.0±1.7	0.5545±0.004	7.0	$8.36 \pm 4.8 \pm 4.8$

5.2 Tests of QCD "15%" Rule

Perturbative QCD predicts[4] that

$$Q_h = \frac{Br(\Psi' \to h)}{Br(J/\psi \to h)} = \frac{Br(\Psi' \to e^+e^-)}{Br(J/\psi \to e^+e^-)} = (14.7 \pm 2.3)\%$$

According to the new measurements of the above branching ratios and the method from the PDG tables[1] to quadratically combine the statistical and systematic errors, we can test QCD "15%" rule, the Q_h's are:

$$Q_{\omega\pi^+\pi^-} = \frac{4.47 \times 10^{-4}}{7.2 \times 10^{-3}} = (6.3 \pm 1.4)\%$$

$$Q_{\omega K^+K^-} = \frac{1.26 \times 10^{-4}}{7.4 \times 10^{-4}} = (17.0 \pm 9.6)\%$$

$$Q_{\phi K^+K^-} = \frac{6.10 \times 10^{-5}}{8.3 \times 10^{-4}} = (7.3 \pm 3.0)\%$$

$$Q_{\phi\pi^+\pi^-} = \frac{1.76 \times 10^{-4}}{8.0 \times 10^{-4}} = (22.0 \pm 5.3)\%$$

$$Q_{\phi f_0} = \frac{6.57 \times 10^{-5}}{3.2 \times 10^{-4}} = (20.5 \pm 8.1)\%$$

$$Q_{\omega p\bar{p}} = \frac{6.00 \times 10^{-5}}{1.3 \times 10^{-3}} = (4.6 \pm 2.2)\%$$

$$Q_{\phi p\bar{p}} = \frac{0.86 \times 10^{-5}}{4.5 \times 10^{-5}} = (18.9 \pm 13.4)\%$$

$$Q_{\pi^+\pi^-\pi^0 p\bar{p}} = \frac{3.85 \times 10^{-4}}{2.3 \times 10^{-3}} = (16.7 \pm 7.1)\%$$

$$Q_{\eta p\bar{p}} = \frac{8.36 \times 10^{-5}}{2.09 \times 10^{-3}} = (4.00 \pm 4.00)\%$$

$$Q_{\eta\pi^+\pi^- p\bar{p}} = \frac{2.58 \times 10^{-4}}{\mathrm{NoPDGdata}} =?$$

Where the corresponding J/ψ decay branching ratios are taken from PDG[1]. From the above Q_h's, we can see that for $\Psi(2S) \to \omega\pi^+\pi^-$, ϕK^+K^-, $\omega p\bar{p}$ and $\eta p\bar{p}$, the ratios of $\Psi(2S)$ hadronic decay branching fractions to those of J/ψ is suppressed at least by a factor of 2 with respect to perturbative QCD predictions, while for ωK^+K^-, $\phi\pi^+\pi^-$, ϕf_0, $\phi p\bar{p}$ and $\pi^0\pi^+\pi^- p\bar{p}$, the ratios are consistent with theoretical predictions within errors.

6 Summary

For the first time, the branching ratios of $\Psi(2S)$ decays into $\omega\pi^+\pi^-$, $\phi\pi^+\pi^-$, ωK^+K^-, ϕK^+K^-, ϕf_0, $\omega p\bar{p}$, $\pi^0\pi^+\pi^- p\bar{p}$, $\eta\pi^+\pi^- p\bar{p}$, $\phi p\bar{p}$ and $\eta p\bar{p}$ are given. Through these measurements, the strong OZI and DOZI violation by a factor of two order of magnitude in $\Psi(2S)$ decays into $\phi\pi^+\pi^-$, $\omega\pi^+\pi^-$, ϕK^+K^- and ωK^+K^- is observed in contrast to the phenomenologically universal $\omega \sim \phi$ mixing model, while this violation is not serious in $\Psi(2S)$ into $\omega p\bar{p}$ and $\phi p\bar{p}$. It shows that this model does not give good interpretation of the $\Psi(2S)$ hadronic decays into ω and ϕ. The results qualitatively accord well with the perturbative QCD and large N_C QCD predictions. But no dynamical and quantitative theories are available, we are hoping for the dynamical and quantitative interpretations for such OZI and DOZI processes.

The QCD "15%" rule is also tested with these newly measured $\Psi(2S)$ decay branching ratios. Among these channels, the ratios Q_h's are suppressed at least by a factor of 2 in $\Psi(2S)$ decays into $\omega\pi^+\pi^-$, ϕK^+K^-, $\omega p\bar{p}$ and $\eta p\bar{p}$, while are consistent with QCD predictions in $\Psi(2S)$ into ωK^+K^-, ϕf_0, $\pi^0\pi^+\pi^- p\bar{p}$, $\phi p\bar{p}$ and $\phi\pi^+\pi^-$ within errors.

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