Decays of the $\psi(2S)$ into hadronic final states containing ω and ϕ mesons

The BES Collaboration

(April 14, 2000)

We report first measurements of branching fractions for $\psi(2S)$ 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 an upper limit for $\eta p\bar{p}$. Strong OZI and DOZI violations in the context of the naive $\omega\sim\phi$ mixing model are observed for $\psi(2S)$ decays into $\omega\pi^+\pi^-$, $\phi\pi^+\pi^-$, ωK^+K^-, ϕK^+K^-; for $\omega p\bar{p}$, $\phi p\bar{p}$, the violation is not so serious and the results are comparable with the semi-quantitative predictions of perturbative QCD and of large N_C QCD. The ratios of $\psi(2S)$ and J/ψ branching fractions to $\omega\pi^+\pi^-$, ϕK^+K^- and $\omega p\bar{p}$ are smaller than perturbative QCD expectations at least by a factor of two, 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 expectations within errors. The measurements are based on a data sample of $(3.79\pm 0.31)\times 10^6$ $\psi(2S)$ decays collected with the BES detector at the Beijing Electron-Positron Collider.

I. INTRODUCTION

In the area of hadronic charmonium decays there exists a longstanding mystery, first revealed by Mark-II Collaboration, known as the $\rho\pi$ puzzle [1]. In perturbative QCD, the charmonium states, J/ψ and $\psi(2S)$, are considered to be nonrelativistic bound systems of charm and anticharm quarks and their decays into light hadrons are expected to be dominated by the annihilation of the $c\bar{c}$ constituents into three gluons. In this simple picture, the partial width for decays into any specific final hadronic state h consisting of light hadrons is proportional to the wave function square $|\psi(0)|^2$ at the origin. Since the ratio of these factors for the $\psi(2S)$ and J/ψ states is very nearly equal to the ratio of the e^+e^- decay widths and the strong coupling constant α_s does not change much between the J/ψ and $\psi(2S)$ masses, perturbative QCD suggests that the ratios of the decay widths for $\psi(2S)$ decays into hadrons to that of J/ψ decays into hadrons can be expressed as: [2]

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

where the leptonic branching fractions are taken from the PDG tables [3]. This is known as the "15% rule." Although the rule works reasonably well for a number of specific decay modes, it fails seriously in the case of $\psi(2S)$ decays to vector-pseudoscalar (VP) $\rho\pi$ and $K^*\bar{K}$ final states. The observed results for $\rho\pi$ and $K^*\bar{K}$, $Q_{\rho\pi} < 0.23\%$ $Q_{K^{*+}K^- + c.c} < 0.64\%$ at $CL = 90\%$ and $Q_{K^{*0}\overline{K^0}+c.c} = (1.7\pm 0.6)\%$, are in substantial contradiction with 15% rule expectations [4]. In addition, the BES group has reported violations of the 15% rule for vector-tensor (VT) decay modes [5]. While a number of theoretical explanations have been proposed to explain this puzzle, none of them are entirely satisfactory [6].

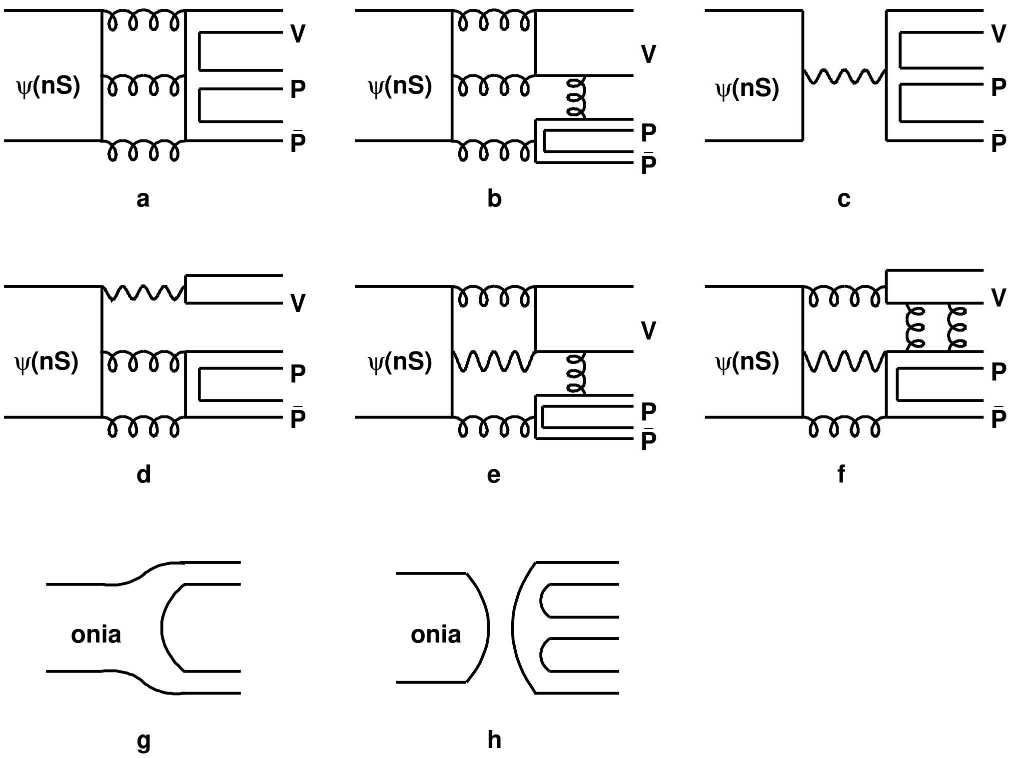

FIG. 1. The lowest-order diagrams for three-body charmonium decays. Charmonium decays into hadrons via (a) ggg, (b) ggg but DOZI suppressed, (c-f) electromagnetic decays into hadrons with (c, d) SOZI and (e, f) DOZI suppressed. Where V stands for vector mesons, P for pseudoscalar mesons.

In addition to their intrinsic interest, charmonium decays provide a good system for the study of the dynamics and spectroscopy of light-quark hadron states. The decays of the J/ψ and $\psi(2S)$ into vector-pseudoscalar-pseudoscalar (VPP) final states are expected to proceed mainly via the sequential processes shown in Fig. 1(a-f). Here, the strong decays via $c\bar{c}$ annihilation into three gluons (Fig. 1a) are suppressed by the Okubo-Zweig-Iizuka (OZI) rule [7], which states that processes with quark lines that are disconnected between the initial and final states (such as those shown in Fig. 1h) are suppressed in comparison to those with connected quark lines (e.g., Fig. 1g). Electromagnetic processes that include a virtual photon (Fig. 1c) can be of comparable strength to OZI-suppressed strong interaction processes. The Doubly OZI-suppressed amplitudes (DOZI, shown in Fig. 1b, e, f) may also contribute to the decays rates via interference with larger, singly OZI-suppressed (SOZI) processes.

In recent years, a substantial cross section for production of ϕ mesons has been observed in OZI-suppressed nucleon-antinucleon annihilation processess [8]. This OZI-suppressed ϕ meson production was explained as being due to the effects of $\omega \sim \phi$ mixing. At the tree level in the $\omega \sim \phi$ mixing model [9], the relative ϕ and ω production rates are expected to be proportional to the deviation of the $\omega \sim \phi$ mixing angle (θ) from its so-called ideal value (θ_i): $(\theta_i - \theta)^2 \sim (1 - 4.2) \times 10^{-3}$; similar expectations obtain for the $f_2'(1525)$ and $f_2(1270)$ tensor mesons [3]. The expectation that singly disconnected SOZI diagrams dominate over doubly disconnected DOZI ones is confirmed from the large ratio $Br(J/\psi \rightarrow \omega f_2)/Br(J/\psi \rightarrow$

$\omega f_2'$) > 20 [3].

The OZI rule has been found to work well for a large number of strong interaction processes involving light quarks and it is expected to work even better for heavy flavors because of the reduced value of the strong interaction coupling constant α_s [2]. In the context of large N_C QCD [10], the decay widths of the OZI-suppressed processes in Fig. 1h are suppressed relative to the allowed ones of Fig. 1g by a factor of ${N_C}^{-2}$. Likewise, the decay widths for DOZI processes are suppressed relative to SOZI ones by the same ${N_C}^{-2}$ factor. While these suppressions are rigorous in the $N_C \to \infty$ limit, there is still no estimate for the degree of reliability of these suppression factors for finite $N_C = 3$,

The application of perturbative QCD to charmonium decays into light-flavor hadrons gives the following semi-quantitative decay width estimates [11]:

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

and

$$\Gamma(J/\psi \to \phi K^+K^-) \simeq \Gamma(J/\psi \to \omega K^+K^-).$$

In addition, because of the small differences of $\alpha_s(\sqrt{s})$ at $\sqrt{s} = m_\psi$ and $m_{\psi(2S)}$, and the different values at the origin for the J/ψ and $\psi(2S)$ wave functions, analogous results can be inferred for $\psi(2S)$ decays:

$$\frac{\Gamma(\psi(2S) \to \phi\pi^+\pi^-)}{\Gamma(\psi(2S) \to \omega\pi^+\pi^-)} > \frac{\Gamma(J/\psi \to \phi\pi^+\pi^-)}{\Gamma(J/\psi \to \omega\pi^+\pi^-)}.$$

In this paper, the first measurement of $\psi(2S)$ decays into $\omega\pi^+\pi^-$, $\phi\pi^+\pi^-$, ωK^+K^-, ϕK^+K^-, $\omega p\bar{p}$, $\phi p\bar{p}$ and ϕf_0, $\pi^0\pi^+\pi^-p\bar{p}$ and $\eta\pi^+\pi^-p\bar{p}$ are presented. The results are compared with existing measurements for the corresponding J/ψ decays.

II. THE BES DETECTOR

The BEijing Spectrometer, BES, is a large solid-angle general purpose magnetic spectrometer that is described in detail in ref. [12]. Charged particle tracking is provided by a main drift chamber (MDC) that has 40 cylindrical layers of drift cells and covers 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). The MDC also provides energy-loss (dE/dx) measurements for each detected track with a resolution of about 11%; this provides π/K separation for particles with momenta below 0.6 GeV/c. An array of 48 scintilation counters surrounding the MDC provides measurement of the time-of-flight (TOF) of charged tracks with a resolution of about 450 ps for hadrons that provides additional information for π/K separation for momenta up to 0.5 GeV/c. Outside of the TOF system is a 12 radiation length thick lead-gas barrel shower counter (BSC) that operates in self-quenching streamer mode and detects electrons and photons over 80% of the total solid angle. The BSC energy resolution is $\sigma_E/E = 0.22/\sqrt{E}$ (E in GeV), and its spatial resolution for photons is $\sigma_\phi = 4.5$ mrad and $\sigma_\theta = 12$ mrad. A solenoidal magnet surrounds the BSC and provides a 0.4 Tesla magnetic field in the central tracking region of the detector. Outside of the solenoidal coil there are three double layers of proportional chambers interspersed with the iron flux return for the magnet that identify muons (MUID) with momenta greater than 0.5 GeV/c. Endcap time-of-flight (ETOF) and shower counters (ESC) cover the forward and backward detector regions. Fast track information from a four-layer central drift chamber (CDC) that is inside the MDC and coaxial with the beampipe together with signals from the TOF scintillators are used to trigger the detector.

III. EVENT SELECTION AND BRANCHING FRACTION MEASUREMENTS

A. Data samples and selected event topologies

The data sample used for this analysis consists of $(3.79 \pm 0.31) \times 10^6$ $\psi(2S)$ decays taken with the BES detector at Beijing Electron Positron Collider (BEPC) at a center-of-mass energy $\sqrt{s} = M_{\psi(2S)}$. The decay channels investigated are $\psi(2S)$ decays into $(\omega, \phi) + (\pi^+\pi^-, K^+K^-, p\bar{p})$, where the ω decays into $\pi^+\pi^-\pi^0$ then π^0 into 2γ, and the ϕ into K^+K^-. We also report measurements of the decays $\psi(2S) \to \pi^+\pi^-\pi^0 p\bar{p}$, $\eta\pi^+\pi^- p\bar{p}$ and ϕf_0, where (π^0, η) decays into $\gamma\gamma$, ϕ into K^+K^- and f_0 into $\pi^+\pi^-$. The final states are four-prong events involving ϕ and four-prong plus at least 2γ events involving ω, η or π^0. (Since, in addition to showers from photons from the event of interest, the shower counters register neutral clusters from secondaries from charged-particle induced showers and from unrelated background processes, we put no limit on the multiplicity of photon candidates in the event.) The values for the branching ratios of the intermediate states used here are taken from the PDG tables [3].

A Monte Carlo phase-space event generator is used in conjunction with a detector simulation program to determine the detection acceptance. Studies indicate that the differences between the acceptance determined using phase space distributions with those using more complex assumptions about the dynamics are small.

B. General selection criteria

Charged tracks are required to be well fit to helices that originate in the vertex region $V_{xy} = \sqrt{V_x^2 + V_y^2} < 1.5$ cm and $|V_z| < 15$ cm and with polar angles in the region $|cos\theta| < 0.8$. Candidate events are required to have four charged tracks with zero total net charge. Flavor-identified charged tracks are required to have a dE/dx value that corresponds to a 3σ separation from other hypotheses. Kinematic fits also provide some particle separation. The kinematic fit and dE/dx information are combined for particle separation. For different particle assignment hypotheses, the one with the smallest value of

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

is selected, where χ^2_{fit} ($\chi^2_{dE/dx}$) is the χ square for the kinematic (dE/dx) fit, and the summation runs over all final charged particles with good helix reconstructed tracks.

Photon candidates are required to register in at least two depth layers in the BSC. For photon reconstruction, we only consider BSC energy clusters that are more than 16^0 away from the nearest charged track in order to reject fake photons produced by charged particle showers, as explained in ref. [13]. In addition, the angle between the photon emission direction and its development direction inside the BSC is required to be less than 37^0. We also require $E_\gamma^{fit} > 60$ MeV, where E_γ^{fit} is the photon energy determined from the kinematic fit.

Events that contain any tracks that are positively identified as electrons or muons are discarded. We also reject events where either the recoil mass or the invariant mass of any oppositely charged particle pair lies within ± 50 MeV of the J/ψ mass. This reduces backgrounds from $\psi(2S) \rightarrow J/\psi X$ cascade processes.

The events are subjected to kinematic fits that impose conservation of energy and momentum constraints. For non-ω events, this corresponds to four constraints (4C). For ω events, the ω mass resolution is improved by the imposition of a fifth constraint (5C) that requires the invariant mass of two photons to have the value m_{π^0}. The confidence levels of the kinematic fits and charged-particle dE/dx are both required to be greater than 1%. In addition, the total χ^2 probability of the kinematic fit plus dE/dx for any hypothesis is required to be greater than that for a background hypothesis. Final state resonances are fit to a Breit-Wigner shape convoluted with Gaussian resolution functions, with polynomial curves used to represent the background.

C. Systematic errors

Systematic errors primarily come from the following sources: 1) uncertainties caused by the event selection criteria; 2) errors of the acceptance and the mass resolution from MC simulation; 3) errors of the total number of $\psi(2S)$ decays in the event sample; and 4) errors of the PDG values of the ϕ, ω, η and π^0 decay branching ratios used in the branching fraction calculations. We evaluate the error from the first source by letting the cuts vary about their nominal values and examining the effects on the final results. For example, we changed confidence level requirement from 1% to 4% and the minimum fitted energy of photon from 60 MeV to 50 MeV. For the error due to the second source, we varied the mass resolution by $\pm 10\%$ from the MC determined values and redued the polar angle acceptance region from $|cos\theta| < 0.8$ to 0.75, etc., and examined how the results changed. The determination of the number of $\psi(2S)$ decays in our data sample and its associated errors are described in detail in ref. [14]. The systematic errors for all the above decay channels listed in Table I are the quadrature sum of the errors thus determined.

D. Specific Channels

1. $\psi(2S) \rightarrow \omega\pi^+\pi^-$

For the $\psi(2S) \rightarrow \omega\pi^+\pi^-$ decay channel, candidate events with the $\gamma\gamma\pi^+\pi^-\pi^+\pi^-$ topology are subjected to a 5-C fit with all pairs of photon candidates tried as a π^0. For events where multiple photon pairs provide acceptable fits, the pair with the highest confidence level is accepted. Events are rejected if the confidence levels of the kinematic and dE/dx fits to the

ωK^+K^- hypothesis are greater than that for $\omega\pi^+\pi^-$. For this channel, the fitted photon energies are required to be $E_\gamma^{fit} > 60$MeV.

Figure 2 shows the $\pi^+\pi^-\pi^0$ mass distribution for accepted events. A prominent ω signal is evident. A fit to the distribution gives 79.3 ± 10.2 signal events and a peak mass of 0.783 ± 0.002 GeV (statistical errors only). The ω mass resolution is 10.4 MeV. The fit results are listed in Table I. Using the MC-determined acceptance of $(5.34 \pm 0.12)\%$, we determine the branching fraction:

$$Br(\psi(2S) \to \omega\pi^+\pi^-) = (4.47 \pm 0.57 \pm 0.54) \times 10^{-4},$$

where the first error is statistical, and the second systematic.

A significant portion of the $\omega\pi^+\pi^-$ signal corresponds to $\psi(2S) \to b_1^\pm\pi^\mp$ decays [15]. To remove this contribution, events with $|m_{\pi^+\pi^-\pi^0} - m_\omega| < 30$ MeV and $|m_{\omega\pi^\pm} - m_{b_1^\pm}| < \Gamma_{b_1}$ (b_1 width) are rejected, in which case 45.6 ± 8.2 events remain. The acceptance for $\omega\pi^+\pi^-$ final state with these $b_1\pi$ removal cuts is $(4.62 \pm 0.12)\%$. This gives a branching ratio for $\psi(2S)$ 3-body decay to $\omega\pi^+\pi^-$:

$$Br(\psi(2S) \to \omega\pi^+\pi^-) = (2.97 \pm 0.53 \pm 0.45) \times 10^{-4},$$

where the sysmatic error includes uncertainties with the cuts used to remove $b_1\pi$ events.

2. $\psi(2S) \to \phi\pi^+\pi^-$

The $\psi(2S) \to \phi\pi^+\pi^-$ decay is observed in the final state topology $\pi^+\pi^-K^+K^-$. The general selection requirements, described above in Sec. III B, are applied to select signal events with the smallest $\chi^2 = \chi^2_{4C-fit} + \sum_i(\chi^2_{i dE/dx})$ for the different particle type hypotheses. To reject backgrounds from other four-charged particle decay modes, the total χ^2 probability from the 4C kinematic fit plus dE/dx is required to be greater than that of $\psi(2S)$ decays into either $K^+K^-K^+K^-$ or $\pi^+\pi^-\pi^+\pi^-$.

The K^+K^- invariant mass distribution is shown in Fig. 3, where a prominent ϕ signal can be seen. A fit to the peak yields 57.4 ± 7.2 events with a peak mass of (1.019 ± 0.001) GeV. Using the MC-determined acceptance of $(17.61 \pm 0.34)\%$, the branching ratio is determined to be:

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

A main component of the $\phi\pi^+\pi^-$ final state is from $\phi f_0(980)$ where the $f_0(980)$ decays into $\pi^+\pi^-$ (see the next subsection). After the $\phi f_0(980)$ contribution is removed by requiring $0.9\ GeV < m_{\pi^+\pi^-} < 1.01$ GeV, 37.3 ± 6.1 $\phi\pi^+\pi^-$ events are observed. In this case the acceptance is $(16.78 \pm 0.26)\%$ and the branching ratio for $\psi(2S)$ 3-body decay into $\phi\pi^+\pi^-$ is:

$$Br(\psi(2S) \to \phi\pi^+\pi^-) = (1.20 \pm 0.19 \pm 0.18) \times 10^{-4},$$

where the systematic error includes uncertainties introduced by the $0.9\ GeV < m_{\pi^+\pi^-} < 1.01$ GeV requirement.

3. $\psi(2S) \to \phi f_0(980)$

Since it is often considered as a candidate for an exotic state, the scalar ($J^{PC} = 0^{++}$) meson $f_0(980)$ is especially intriguing both experimentally and theoretically [16]. Here we observe an $f_0(980)$ signal in the invariant mass distribution of $\pi^+\pi^-$ pairs recoiling against a ϕ, as shown in Fig. 4. A Breit-Wigner fit gives 20.3 ± 5.2 $\phi f_0(980)$ signals with a peak mass of (0.983 ± 0.008) GeV, the signal significance is 5.4σ. Using an acceptance of $(21.27 \pm 0.40)\%$, which was calculated from a MC simulation using a width of $\Gamma_{f_0} = 50MeV$ [17], MC simulation, we determine the branching fraction

$$Br(\psi(2S) \to \phi f_0) = (6.6 \pm 1.7 \pm 0.8) \times 10^{-5}.$$

4. $\psi(2S) \to \omega K^+K^-$

For the $\psi(2S) \to \omega K^+K^-$ decay channel, the final state is $\gamma\gamma\pi^+\pi^-K^+K^-$. As discussed in Sec. III B, a 5C kinematic fit is performed with all pairs of photon candidates forming a π^0 and all possible π/K assignments for the charged tracks. The assignments with the smallest total $\chi^2 = \chi^2_{5C-fit} + \sum_i(\chi^2_{i dE/dx})$ that also pass the general cuts are selected. The combined dE/dx and 5C fit confidence level is required to be greater than that for $\omega\pi^+\pi^-$ in order to reject this possible background. We also require the $\pi^+\pi^-$ invariant mass from ω decay should be less than $0.65GeV/c^2$.

Figure 5 shows the $\pi^+\pi^-\pi^0$ invariant mass for ωK^+K^- candidates. A fit gives 16.8 ± 5.6 ω signals with a peak mass value of (0.782 ± 0.006) GeV; the signal significance is 4.2σ. For this mode, the MC-determined acceptance is $(3.86 \pm 0.11)\%$ and the measured branching ratio is:

$$Br(\psi(2S) \to \omega K^+K^-) = (1.31 \pm 0.44 \pm 0.39) \times 10^{-4}.$$

5. $\psi(2S) \to \phi K^+K^-$

The final state $K^+K^-K^+K^-$ is used to study $\psi(2S) \to \phi K^+K^-$. A 4C kinematic fit is done for the events passing the general cuts listed above (see Sec. III B). To remove possible backgrounds, the combined 4C fit plus dE/dx confidence level is required to be greater than those for $\psi(2S) \to \pi^+\pi^-K^+K^-, \pi^+\pi^-\pi^+\pi^-$.

Figure 6 shows the K^+K^- invariant mass distribution. Here there is a ϕ signal with 18.1 ± 5.3 events, corresponding to a 3.9σ significance level. The MC-determined acceptance is $(15.94 \pm 0.26)\%$ and the decay branching fraction is

$$Br(\psi(2S) \to \phi K^+K^-) = (6.1 \pm 1.8 \pm 1.5) \times 10^{-5}.$$

E. $\psi(2S) \to \gamma\gamma\pi^+\pi^-p\bar{p}$ final states

1. $\psi(2S) \to \omega p\bar{p}, \eta p\bar{p}$

The $\psi(2S) \to \omega p\bar{p}$ and $\psi(2S) \to \eta p\bar{p}$ processes have the same event topology $\gamma\gamma\pi^+\pi^-p\bar{p}$, where the ω and η decay into $\pi^+\pi^-\pi^0$ and the π^0 into $\gamma\gamma$. Each candidate event is subjected to 5C fits with all pairs of photon candidates are associated with the π^0 and all possible π/p assignments are tried. The assignment with the highest combined kinematic fit and dE/dx confidence level ($\geq 1\%$) is selected. Events where the confidence level for $\psi(2S) \to \omega K^+K^-$ or $\omega\pi^+\pi^-$ is higher are rejected. For this channel, the fitted energies of both of the photons are required to be greater than 60 MeV.

A fit to the $\pi^+\pi^-\pi^0$ mass distribution is shown in Fig. 7. An 12.3 ± 4.3 event ω signal is observed with a 4.0σ significance. The fitted ω mass is (0.779 ± 0.006) GeV. Using the MC-determined acceptance of $(5.52 \pm 0.13)\%$, we measure a branching fraction of:

$$Br(\psi(2S) \to \omega p\bar{p}) = (6.7 \pm 2.3 \pm 1.4) \times 10^{-5}.$$

There are three events with $\pi^+\pi^-\pi^0$ mass centered at M_η. Taking all three as possible η signals and using the acceptance $\epsilon = (4.13 \pm 0.11)\%$, we derive a 90% confidence level upper limit on the branching fraction of

$$Br(\psi(2S) \to \eta p\bar{p}) < 1.9 \times 10^{-4}.$$

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

The $\psi(2S) \to \pi^0\pi^+\pi^- p\bar{p}$ and $\eta\pi^+\pi^- p\bar{p}$ channels where the π^0 and η decay into $\gamma\gamma$ have the same final states as described above in Sec. III E 1. We use the same method except that here only 4C fits are used. Prominent π^0 and η signals are apparent in the $\gamma\gamma$ mass plots shown in Fig. 8. A fit yields a 101.6 ± 10.5 event π^0 signal and a 35.0 ± 9.2 event η signal. The acceptances are $(7.43 \pm 0.19)\%$ for $\psi(2S) \to \pi^0\pi^+\pi^- p\bar{p}$ and $(9.14 \pm 0.20)\%$ for $\psi(2S) \to \eta\pi^+\pi^- p\bar{p}$ and the measured branching fractions are:

$$Br(\psi(2S) \to \pi^0\pi^+\pi^- p\bar{p}) = (3.65 \pm 0.38 \pm 0.55) \times 10^{-4},$$

$$Br(\psi(2S) \to \eta\pi^+\pi^- p\bar{p}) = (2.58 \pm 0.68 \pm 0.73) \times 10^{-4}.$$

F. $\psi(2S) \to \phi p\bar{p}$

For $\psi(2S) \to \phi p\bar{p}$, the method is same as for $\psi(2S) \to \phi\pi^+\pi^-$ (see Sec. III D 2). In the K^+K^- invariant mass distribution, shown in Fig. 9, there are three events in the ϕ region ($1.0 < m_{K^+K^-} < 1.04$ GeV). Since the BES π/p and K/p separation is quite reliable, we consider this as a real signal. Here the acceptance is $(18.69 \pm 0.28)\%$ and the branching ratio is

$$Br(\psi(2S) \to \phi p\bar{p}) = (0.86 \pm 0.50 \pm 0.20) \times 10^{-5}.$$

IV. RESULTS AND DISCUSSIONS

The results are summarized in Table I. Here the fitted masses for the ϕ and ω resonances agree within errors with the PDG values [3].

TABLE I. Measurement of the $\psi(2S)$ decay branching ratios. (Note: We use Γ_{f_0}=50MeV and only the statistical errors are listed for the fitted resonance masses. The upper limit is at the 90% confidence level.)

$\psi(2S)\ \Rightarrow$	ϵ_{acc}	N_{obs}	M_R(GeV)	σ_m(MeV)	Br($\times 10^{-5}$)
$\omega\pi^+\pi^-$	5.34 ± 0.12	79.3±10.2	0.783±0.002	10.3	$44.7 \pm 5.7 \pm 5.4$
ωK^+K^-	3.86 ± 0.11	16.8±5.6	0.782±0.006	12.0	$13.1 \pm 4.4 \pm 3.9$
$\phi\pi^+\pi^-$	17.61 ± 0.34	57.4±7.2	1.019± 0.001	2.1	$17.6 \pm 2.2 \pm 2.4$
ϕK^+K^-	15.94 ± 0.26	18.1± 5.3	1.019±0.002	2.4	$6.1 \pm 1.8 \pm 1.5$
ϕf_0	21.27 ± 0.40	20.3±5.2	0.983±0.008	9.4	$6.6 \pm 1.7 \pm 0.8$
$\omega p\bar{p}$	5.52 ± 0.13	12.3±4.3	0.779±0.006	10.9	$6.7 \pm 2.3 \pm 1.4$
$\phi p\bar{p}$	18.69 ± 0.28	3.0±1.7		2.2	$0.86 \pm 0.50 \pm 0.20$
$\pi^+\pi^-\pi^0 p\bar{p}$	7.43 ± 0.19	101.6±10.5	0.135 ± 0.002	12.2	$36.5\pm3.8 \pm 5.5$
$\eta\pi^+\pi^- p\bar{p}$	9.14 ± 0.20	35.0±9.2	0.537±0.006	18.7	$25.8\pm6.8 \pm 7.3$
$\eta p\bar{p}$	4.13 ± 0.11	3.0		7.0	$< 19@CL = 90\%$

A. The OZI rule

These results can be used to test the $\omega \sim \phi$ mixing model for OZI-rule breaking as well as the 15% rule. The ratios of the branching fractions of $\psi(2S) \to \phi X$ to those of $\psi(2S) \to \omega X$ for the channels involving ω and ϕ are:

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

$$R_{(\phi K^+K^-/\omega K^+K^-)} = \frac{Br(\psi(2S) \to \phi K^+K^-)}{Br(\psi(2S) \to \omega K^+K^-)} = (46.6 \pm 20.8 \pm 18.0)\%$$

$$R_{(\phi p\bar{p}/\omega p\bar{p})} = \frac{Br(\psi(2S) \to \phi p\bar{p})}{Br(\psi(2S) \to \omega p\bar{p})} = (12.8 \pm 8.7 \pm 4.0)\%$$

A strong OZI violation that is about two orders of magnitude above the prediction of the naive $\omega \sim \phi$ mixing model is observed for $\psi(2S) \to \phi\pi^+\pi^-$, $\omega\pi^+\pi^-$, ϕK^+K^-, ωK^+K^-. In contrast, for $\psi(2S) \to \omega p\bar{p}, \phi p\bar{p}$, the violation is not so serious. Moreover, a strong, nearly two order of magnitude DOZI violation is observed for $\psi(2S) \to \phi\pi^+\pi^-$ and $\omega\pi^+\pi^-$. For the same DOZI-violating processes in J/ψ decays, the factor is

$$\frac{Br(J/\psi \to \phi\pi^+\pi^-)}{Br(J/\psi \to \omega\pi^+\pi^-)} = (11.1 \pm 2.3)\%.$$

Thus, the DOZI violation is much stronger in $\psi(2S)$ decays than in J/ψ decays. These results are comparable with the semi-quantitative predictions of the perturbative QCD and of large N_C QCD.

The comparisons show that the naive $\omega \sim \phi$ mixing model poorly describes $\psi(2S)$ hadronic decays involving ω and ϕ. From this we can conclude that ϕ production in $\psi(2S)$ decays does not proceed via $\omega \sim \phi$ mixing. Perturbative QCD and large N_C QCD give a semi-quantitative description of these processes.

B. Tests of the 15% Rule

Based on the new measurement of the branching ratios for $\psi(2S)$ listed in Table I, the 15% rule is tested. The Q_h values defined above in Sec. I are listed for the above channels in Table II.

TABLE II. Q_h values for $\psi(2S)$ and J/ψ hadronic decays

decay channels	$Br_{\psi(2S)}(\times 10^{-5})$	$Br_{J/\psi}(\times 10^{-4})$	$Q_h = \frac{Br(\psi(2S)\to h)}{Br(J/\psi \to h)}$
$\omega\pi^+\pi^-$	$44.7 \pm 5.7 \pm 5.4$	72.0 ± 10.0	$(6.3 \pm 1.4)\%$
ωK^+K^-	$13.1 \pm 4.4 \pm 3.9$	7.4 ± 2.4	(17.7 ± 9.8)
$\phi\pi^+\pi^-$	$17.6 \pm 2.2 \pm 2.4$	8.0 ± 1.2	$(22.0 \pm 5.3)\%$
ϕK^+K^-	$6.1 \pm 1.8 \pm 1.5$	8.3 ± 1.3	$(7.3 \pm 3.0)\%$
ϕf_0	$6.6 \pm 1.7 \pm 0.8$	3.2 ± 0.9	$20.5 \pm 8.1)\%$
$\omega p\bar{p}$	$6.7 \pm 2.3 \pm 1.4$	13.0 ± 2.5	$(5.2 \pm 2.3)\%$
$\phi p\bar{p}$	$0.86 \pm 0.50 \pm 0.20$	0.45 ± 0.15	$(18.9 \pm 13.4)\%$
$\pi^+\pi^-\pi^0 p\bar{p}$	$36.5 \pm 3.8 \pm 5.5$	23.0 ± 9.0	$(15.9 \pm 6.9)\%$
$\eta\pi^+\pi^- p\bar{p}$	$25.8 \pm 6.8 \pm 7.3$	no data	?
$\eta p\bar{p}$	< 19@CL = 90%	20.9 ± 1.8	9% @CL = 90%

Here the corresponding J/ψ decay branching ratios are taken from the PDG tables [3]. From the above Q_h values, it can be seen that for $\psi(2S) \to \omega\pi^+\pi^-$, ϕK^+K^- and $\omega p\bar{p}$, the ratios of $\psi(2S)$ hadronic decay branching fractions to those of J/ψ are suppressed by at least a factor of two with respect to the 15% rule expectations, 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 within errors with the rule. Phenomenologically, the suppression for $\psi(2S) \to \omega\pi^+\pi^-$ can be attributed to the suppression of $\psi(2S) \to \omega f_2(1270)$, which is a quite strong mode for J/ψ decays, as reported previously [5]. The dynamical reason for the suppression of $\psi(2S) \to \omega f_2(1270)$ is unknown. When the $Br(J/\psi \to b_1^\pm \pi^\mp)$ and $Br(J/\psi \to \omega f_2)$ channels are subtracted from $Br(J/\psi \to \omega\pi^+\pi^-)$ and $\psi(2S) \to b_1\pi$ from $\psi(2S) \to \omega\pi^+\pi^-$, see Sec. III D 1, the corresponding Q_h is:

$$Q_{\{\omega\pi^+\pi^-\}_{nonresonance}} = \frac{(2.97 \pm 0.70) \times 10^{-4}}{(1.77 \pm 0.46) \times 10^{-3}} = (16.8 \pm 5.9)\%,$$

which is in agreement with the 15% rule.

V. SUMMARY

The branching ratios for $\psi(2S)$ 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 an upper limit for $\eta p\bar{p}$ are reported for the first time. These measurements indicate strong, two-order-of-magnitude violations of the OZI and DOZI rules for $\psi(2S)$ decays into $\phi\pi^+\pi^-$, $\omega\pi^+\pi^-$, ϕK^+K^- and ωK^+K^-, which disagree with expectations of the phenomenologically universal $\omega \sim \phi$ mixing model. These violations are not so serious for $\psi(2S)$ decays into $\omega p\bar{p}$ and $\phi p\bar{p}$. These results indicate that $\omega \sim \phi$ mixing model does not provide a good description for $\psi(2S)$ hadronic decays into ω and ϕ mesons, and we can conclude that ϕ production in $\psi(2S)$ decays does not occur via $\omega \sim \phi$ mixing. These results agree well with the perturbative QCD and large N_C QCD predictions.

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

ACKNOWLEDGMENTS

We acknowledge the strong efforts of the BEPC staff and the helpful assistance we received from the members of the IHEP computing center. The work of the BES Collaboration is supported in part by the National Natural Science Foundation of China under Contract No. 19991480 and the Chinese Academy of Sciences under contract No. KJ95 T-03, and by the Department of Energy under Contract Nos. DE-FG03-92ER40701 (Caltech), DE-FG03-93ER40788 (Colorado State University), DE-AC03-76SF00515 (SLAC), DE-FG03-91ER40679 (UC Irvine), DE-FG03-94ER40833 (U Hawaii), DE-FG03-95ER40925 (UT Dallas).

[1] M. E. B. Franklin et al., Phys. Rev. Lett. **51**, 963 (1983).

[2] T. Applequist and D. Politzer Phys. Rev. Lett. **34**, 43 (1975).

[3] Particle Data Group, Caso et al., Eur. Phys. J. **C3** (1998)1; here $Br(f_0(980) \to \pi\pi) = (78.1 \pm 2.4)\%$ is cited from R. M. Barnet et al., Phys. Rev. **D54**, 1 (1996) and $Br(J/\psi \to \omega K^+K^-) = (7.4 \pm 0.7 \pm 2.3) \times 10^{-4}$ and $Br(J/\psi \to \phi K^+K^-) = (8.3 \pm 0.3 \pm 1.3) \times 10^{-4}$ from A. Falvard et al., Phys. Rev. **D38**, 2706 (1988) which was cited by Eur. Phys. J. **C3** (1998)1. Eur. Phys. J.**C3** (1998) gives the averages of $Br(J/\psi \to \omega K^+K^-)$ and $Br(J/\psi \to K_s^0K_s^0)$ and of $Br(J/\psi \to \phi K^+K^-)$ and $Br(J/\psi \to \phi K_s^0K_s^0)$ from Phys. Rev. **D38**, 2706 (1988).

[4] Y. S. Zhu, in Proceedings of the 28th International Conference on High Energy Physics, ed. Z. Adjuk and A. K. Wroblewski, World Scientific, 1997.

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

[6] W. S. Hou and A. Soni, Phys. Rev. Lett. **50**, 569 (1983);
G. Karl and W. Roberts, Phys. Lett. **B144**, 243 (1984);
S. J. Brodsky et al., Phys. Rev. Lett. **59**, 631 (1987);
M. Chaichian et al., Nucl. Phys. **B323**, 75 (1989);
S. S. Pinsky, Phys. Lett. **B236**, 479 (1990);
X. Q. Li et al., Phys. Rev. **D55**, 1241 (1997);
S. J. Brodsky and M. Karliner, Phys. Rev. Lett. **78**, 468 (1997);
Yu-Qi Chen and Eric Braaten, Phys. Rev. Lett. **80**, 5060 (1998).

[7] S. Okubo, Phys. Lett. **B5**, 165 (1963); G. Zweig, CERN-preprints CERN-TH-401,402,412(1964); J. Iizuka, Prog. Theor. Phys. Suppl., **21** (1966) 37.

[8] C. Amsler et al., Phys. Lett. **B346**, 363 (1995); A. Bertin et al., Phys. Lett. **B388**, 450 (1996); A. Ferrer et al., Phys. Lett. **B394**, 395 (1997).

[9] V. E. Markushin and M. P. Locher, Eur. Phys. J. **A1**,91 (1998); V. E. Markushin, Nucl. Phys. Proc. Suppl. **56A**, 303 (1997); B. S. Zou, Phys. Atom. Nucl. **59**, 1427 (1996) and references therein.

[10] R. E. Marshak, *Conceptual Foundations of Modern Particle Physics*, **Sec. 5.4b**, *Large N_C limit in QCD and the OZI rule*, World Scientific, 1993.

[11] C. Gilain and F. Hayot, Nuovo Cimento **A41** (1977) 271.

[12] J. Z. Bai et al., BES collab., Nucl. Inst. and Meths. **A344**, 319 (1994).

[13] J. Z. Bai et al., BES collab.,Phys. Rev. **D60**, 072001 (1999).

[14] J. Z. Bai et al., BES collab.,Phys. Rev. **D58**, 092006 (1998)

[15] J. Z. Bai et al., BES collab.,Phys. Rev. Lett. **83**, 1918 (1999).

[16] N.N. Achasov, hep-ph/9803292 and references therein; M. C. Birse et al., editors, HADRON'95, pp454-456, the 6th International Conference on Hadron Spectroscopy, Manchester, UK, Jul 10 - 14, 1995; M. Harada et al., Phys. Rev. **D54**, 1991 (1996), and references therein; N. A.

Törnqvist, Zeit. Physik **C68**, 291 (1993); C. A. Dominguez and N. Paver, Zeit. Physik **C39**, 39 (1988); G. Janssen et al., Phys. Rev. **D52**, 2690 (1995).

[17] M. P. Locher, V. E. Markushin and H. Q. Zheng, Eur. Phys. J. **C4**, 317(1998), the paper cited $\Gamma_{f_0} = 47 \pm 9 MeV$ from Review of Particle Physics, Phys. Rev. **D54**, 1 (1996) [3]; P. Lebrun et al, FERMILAB-CONF-97-388-E; A. A. Kondashov, hep-ph/9811207.

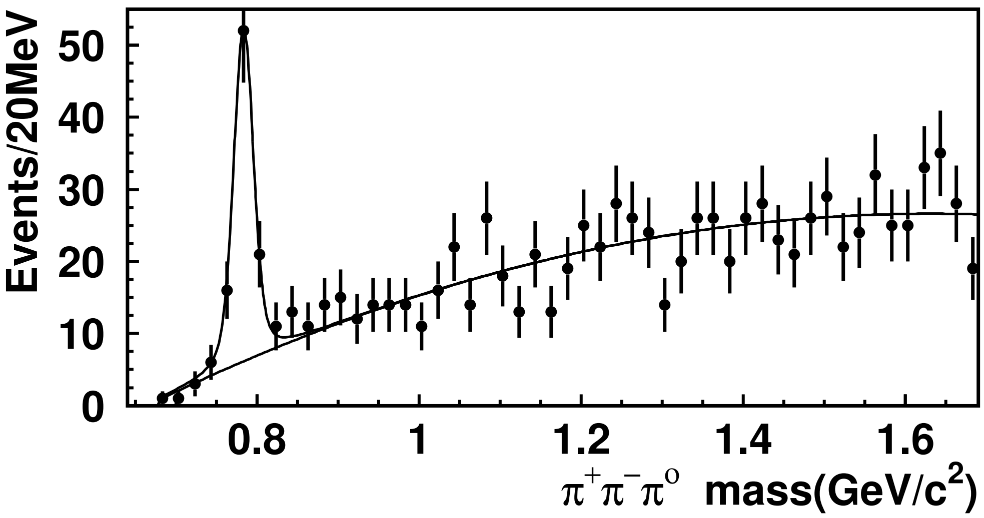

FIG. 2. The $\pi^+\pi^-\pi^0$ mass distribution for candidate $\psi(2S) \to \omega\pi^+\pi^-$ events (4 entries per event) . The curve is the result of a fit to a Breit-Wigner convoluted with a Gaussian mass resolution function plus a second order polynomial.

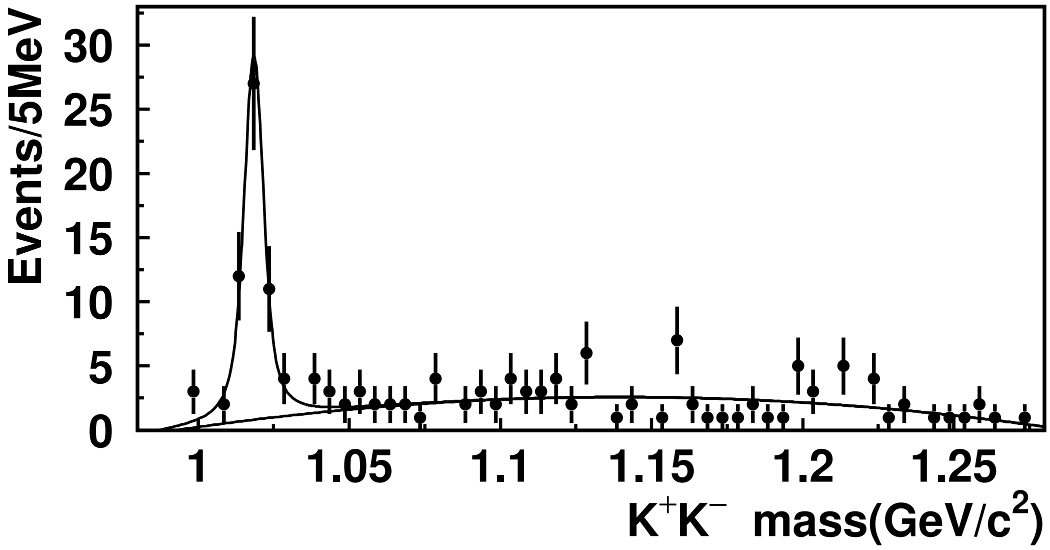

FIG. 3. The K^+K^- invariant mass distribution for candidate $\psi(2S) \to \phi\pi^+\pi^-$ events.

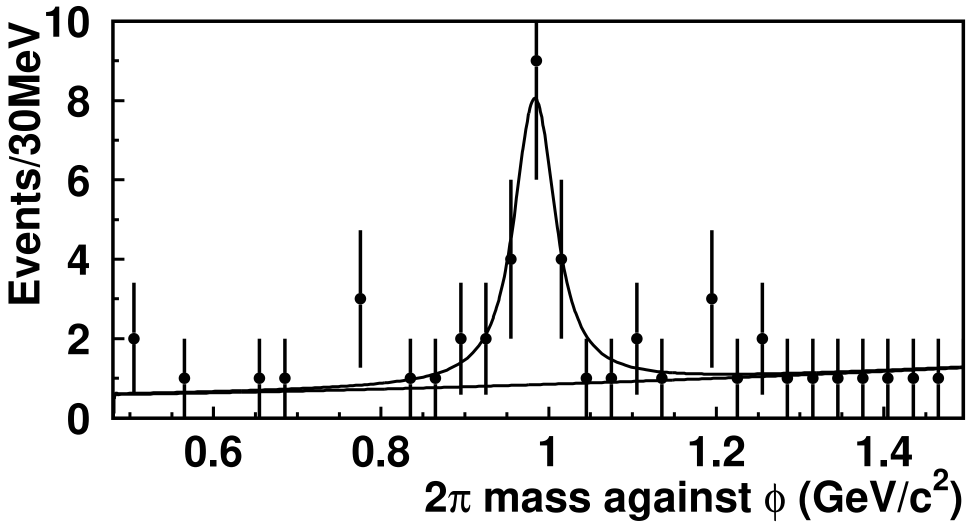

FIG. 4. The invariant mass distribution for $\pi^+\pi^-$ pairs recoiling against ϕ mesons in $\psi(2S) \to \phi\pi^+\pi^-$ events.

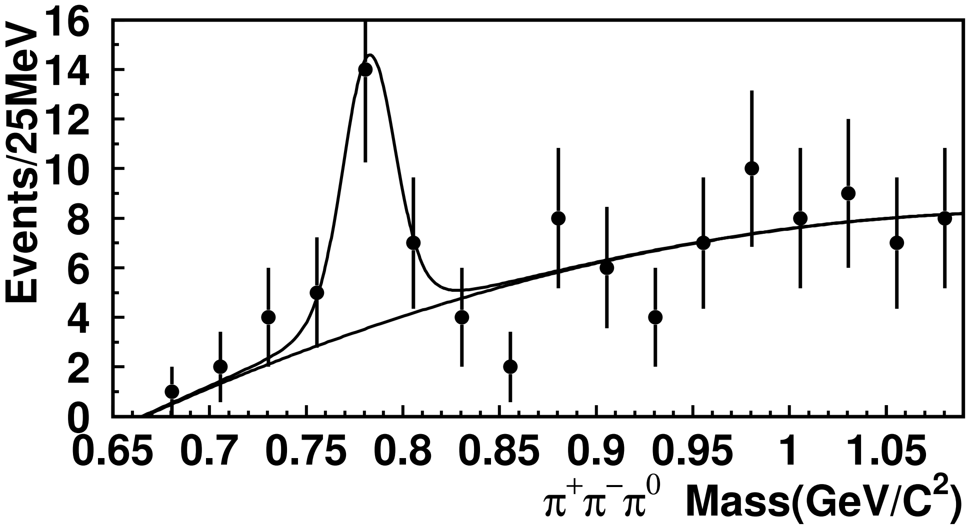

FIG. 5. The $\pi^+\pi^-\pi^0$ invariant mass distribution for candidate $\psi(2S) \to \omega K^+K^-$ events.

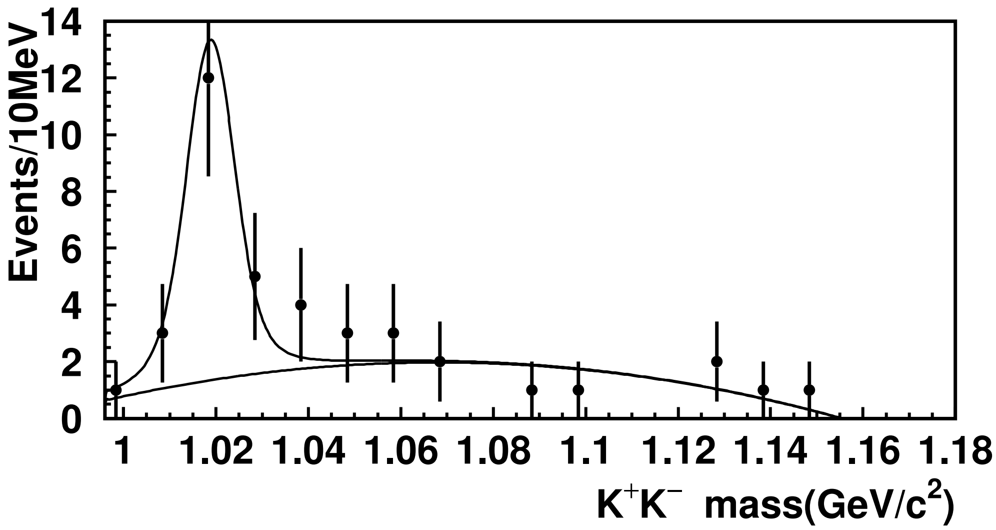

FIG. 6. The K^+K^- invariant mass distribution for candidate $\psi(2S) \to \phi K^+K^-$ events (4 entries per event).

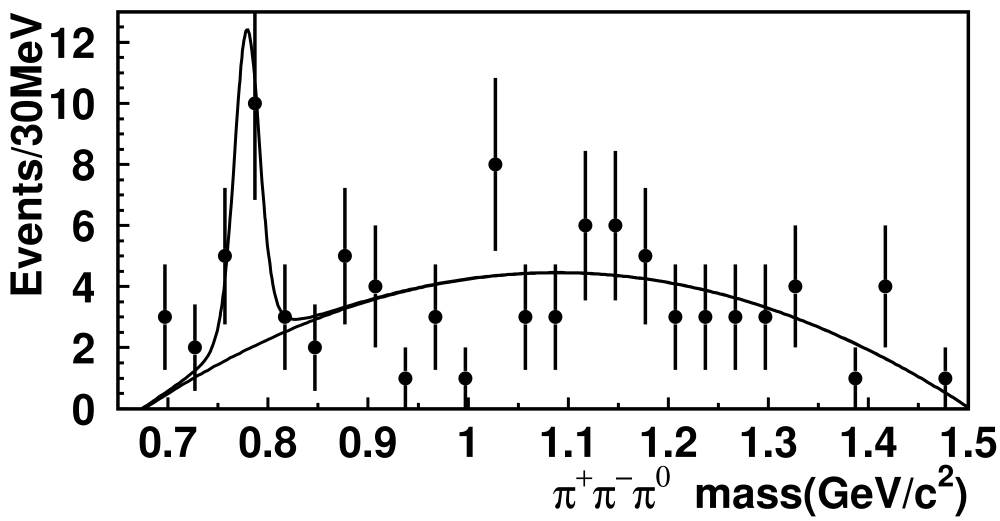

FIG. 7. The $\pi^+\pi^-\pi^0$ invariant mass distribution for candidate $\psi(2S) \to \omega p\bar{p}$ events.

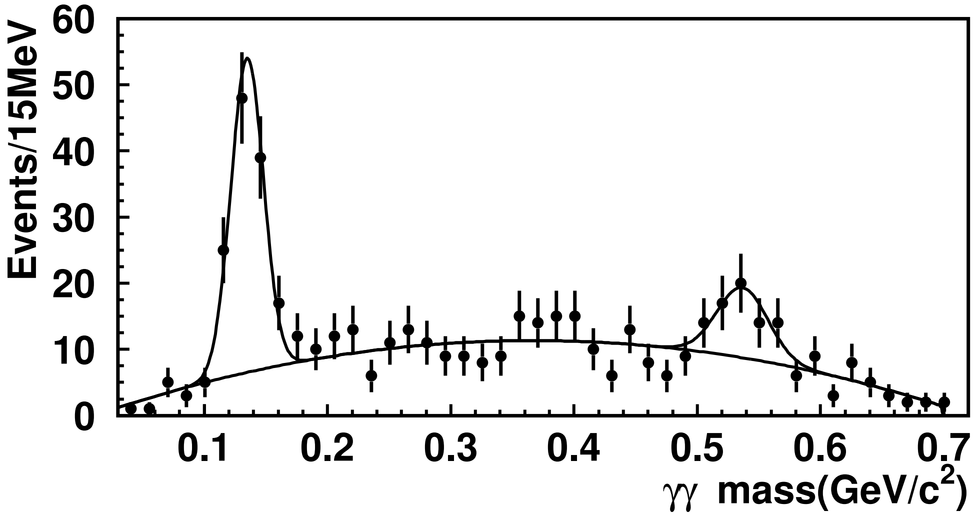

FIG. 8. The $\gamma\gamma$ invariant mass for candidate $\psi(2S) \to (\pi^0, \eta)\pi^+\pi^- p\bar{p}$ events.

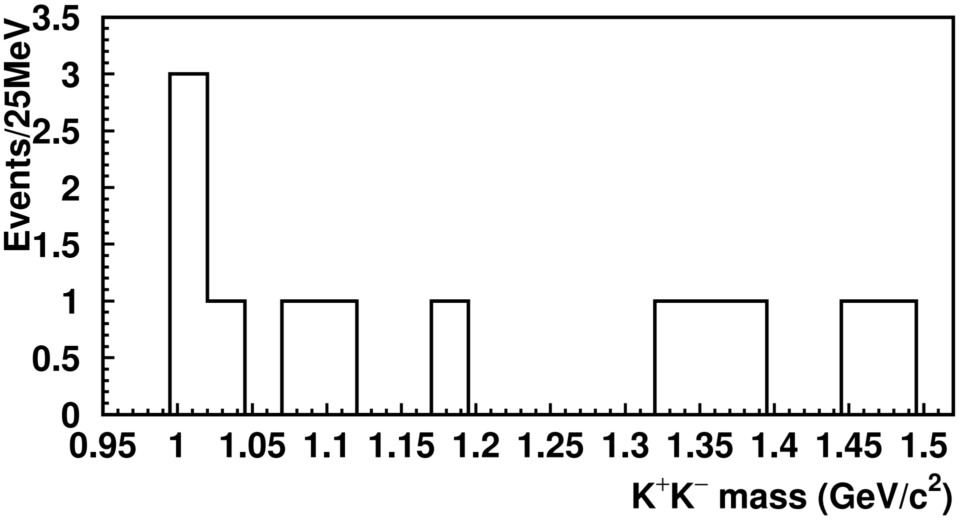

FIG. 9. The K^+K^- invariant mass distribution for candidate $\psi(2S) \to \phi p\bar{p}$ events.