Charmonium Decays to Axialvector plus Pseudoscalar Mesons

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A sample of 3.79 million $\psi(2S)$ decays observed in the BES detector is used to study the process $\psi(2S) \to$ axialvector plus pseudoscalar mesons. The branching fraction for the decay $\psi(2S) \to b_1^{\pm}(1235)\pi^{\mp}$ agrees with expectations based on scaling the corresponding $J/\psi(1S)$ branching fraction. There is strong evidence for $\psi(2S) \to K_1^{\pm}(1270)K^{\mp}$ but not for $\psi(2S) \to K_1^{\pm}(1400)K^{\mp}$, in contradiction to expectations from strict flavor-SU(3) symmetry. We report first measurements of a branching ratio for the former and an upper limit for the latter. A sample of J/ψ decays from the cascade process $\psi(2S) \to \pi^+\pi^- J/\psi$ is used to measure a branching fraction for $J/\psi(1S) \to K_1^{\pm}(1400)K^{\mp}$ decays that exceeds, and an upper limit for $\mathcal{B}(J/\psi(1S) \to K_1^{\pm}(1270)K^{\mp})$ that is below, expectations based on the $\psi(2S)$ results. This contrasting behavior between the J/ψ and the $\psi(2S)$ cannot be accommodated by an adjustment to the singlet-triplet axialvector mixing angle.

I. MOTIVATION

A. The 14% rule for hadronic $\psi(2S)$ decays

In perturbative QCD, the dominant process for hadronic decays of both the J/ψ and the $\psi(2S)$ is annihilation into three gluons followed by the hadronization of these gluons into physically observable hadrons. The similarity between the parton-level final states has led to the conjecture that ratio of the J/ψ and $\psi(2S)$ decay branching fractions into any exclusive final state X_h is given by the ratio of the square of the wave function at the origin of the constituent $c\overline{c}$ quark state, which is well determined from the dilepton decay rates [1]:

$$\frac{\mathcal{B}[\psi(2S) \to X_h]}{\mathcal{B}[J/\psi \to X_h]} \simeq \frac{\mathcal{B}[\psi(2S) \to e^+e^-]}{\mathcal{B}[J/\psi \to e^+e^-]} = 0.141 \pm 0.012.$$

This conjecture is sometimes referred to as *the 14% rule* [10]. Although this conjecture seems to work reasonably well for a number of decay channels, it fails badly in

the case of $\psi(2S)$ two-body decays to vector plus pseudoscalar meson (VP) final states—the decay $\psi(2S) \to \rho\pi$ is suppressed relative to 14% rule expectations by more than a factor of fifty [2,3]. This conundrum is commonly called the $\rho\pi$ puzzle [4]. In addition, the BES group has reported suppressions by factors of at least five in the vector plus tensor meson (VT) final states: $K^*\overline{K_2^*}$, ρa_2, ωf_2 and $\phi f_2'$ [5]. To date, no convincing evidence has been uncovered for hadronic $\psi(2S)$ decays that are enhanced relative to 14%-rule expectations. Since at least one explanation for the $\rho\pi$ puzzle involves a mechanism that suppresses all $\psi(2S)$ decays to lowest lying two-body mesons final states [6], it is useful to examine all possibilities. Here we report first measurements of $\psi(2S)$ decays to axialvector plus pseudoscalar mesons (AP).

B. The axialvector meson octets

There are two lowest-lying axialvector-meson octets. These correspond to the singlet ($^1P_1$) and triplet ($^3P_1$) spin configurations of two quarks in a p-wave orbital angular momentum state. The non-strange $I = 1$ members of the two octets have opposite G-parity: the $b_1(1235)$ is in the $^1P_1$ octet and has $G = +1$, while the $a_1(1260)$ is in the $^3P_1$ octet and has $G = -1$. Since the strong decays of the J/ψ and $\psi(2S)$ conserve G-parity, decays to the axialvector pseudoscalar (AP) pair $b_1\pi$ are allowed and seen in J/ψ decays; decays to $a_1\pi$ final states are forbidden and not seen in J/ψ decays.

The strange members of the $^3P_1$ and $^1P_1$ octets, the K_A and K_B, respectively, are mixtures of the observed physical states, the $K_1(1270)$ and the $K_1(1400)$, where

$$K_A = \cos\theta K_1(1400) + \sin\theta K_1(1270) \quad (1)$$
$$K_B = \cos\theta K_1(1270) - \sin\theta K_1(1400), \quad (2)$$

and the mixing angle is near $\theta \simeq 45^0$ [7]. The dominant $K_1(1270)$ decay mode is to $K\rho$ (Br $= 42 \pm 6\%$); the $K_1(1400)$ decays almost always to $K^*\pi$ (Br $= 94 \pm 6\%$).

In the limit of strict flavor-SU(3) symmetry, the amplitudes for two-body decays to conjugate mesons in the same pair of octets should be equal. Thus, since decays to $a_1\pi$ are forbidden by G-parity, decays to $K_A\overline{K}$ are disallowed by SU(3) and one expects relatively pure $K_B\overline{K}$ final states in J/ψ and $\psi(2S)$ decays. And, since $\theta \simeq 45^0$, there should be roughly equal amounts of $K_1(1270)$ and $K_1(1400)$.

II. THE BES DETECTOR

This analysis is based on a sample of (3.79 ± 0.31) million $e^+e^- \to \psi(2S)$ events collected in the BES detector at the BEPC storage ring of the Institute of High Energy Physics in Beijing [9]. The BES detector is described in some detail in ref. [8]. The features that are most important for the analysis reported here are the 40-layer main cylindrical drift chamber (MDC), the 48-scintillation counter time-of-flight (TOF) system, and the 12-layer lead-gas barrel electromagnetic shower counter (BSC). These are all situated in a 0.45 T solenoidal magnetic field. Charged particle track trajectories are measured in the MDC with a momentum resolution of $2.1\%\ \sqrt{1+p^2(GeV)}$. The directions and energies of high energy γ-rays are measured in the BSC with angular and energy resolutions of $\sigma_{\phi,\theta} \simeq 5$ mrad and $\sigma_E/E = 0.22/\sqrt{E(GeV)}$, respectively. Particle identification is provided by drift chamber dE/dx measurements and from particle velocities as determined from the TOF system. For this analysis, we only use photons and charged tracks that are in the polar angle region $|\cos\theta| \leq 0.8$. This restricts the analysis to particles that traverse all 40 layers of the MDC and are well contained in the BSC. For each charged track, the dE/dx and TOF information is used to determine the probability that the track is consistent with being a kaon; tracks with a probability of more than 10% are considered candidate kaons, otherwise they are considered to be pions. The particle momentum measurements and identification assignments are further refined by the application of four- (4C) and five-constraint (5C) kinematic fits.

III. RESULTS

A. Determination of $\mathcal{B}(\psi(2S) \to b_1\pi)$

Since the dominant decay mode of the b_1 is $b_1 \to \omega\pi$, we apply a five constraint kinematic fit to events of the type

$$\psi(2S) \to \pi^+\pi^-\pi^+\pi^-\gamma\gamma,$$

where the $\gamma\gamma$ invariant mass is further constrained to be equal to $M_{\pi 0}$. The $\pi^+\pi^-\pi^0$ mass distribution for events that pass the 5-C fit is shown in Fig. 1a, where there is a prominent $\omega(782)$ peak. We identify $\pi^+\pi^-\pi^0$ combinations with invariant mass in the range $M_{\pi^+\pi^-\pi^0} = M_\omega \pm 40$ MeV as ω candidates. In events with more than one candidate ω, we use the one with mass closest to M_ω.

Figure 1b shows the $\omega\pi^\pm$ mass distribution for events where the recoiling $\pi^+\pi^-$ pair has an invariant mass greater than 1.55 GeV. The latter requirement eliminates any possible contamination from ωf_2 final states. The peak in Fig. 1b is well fit with a s-wave Breit Wigner function with mass and width fixed at the PDG values for the b_1 ($M_{b_1} = 1.232$ and $\Gamma_{b_1} = 0.142$ GeV) and a background shape that has a phase-space behaviour at threshold that evolves to a constant level at higher masses. There are 83.9 ± 12.7 in the fitted b_1 meson peak.

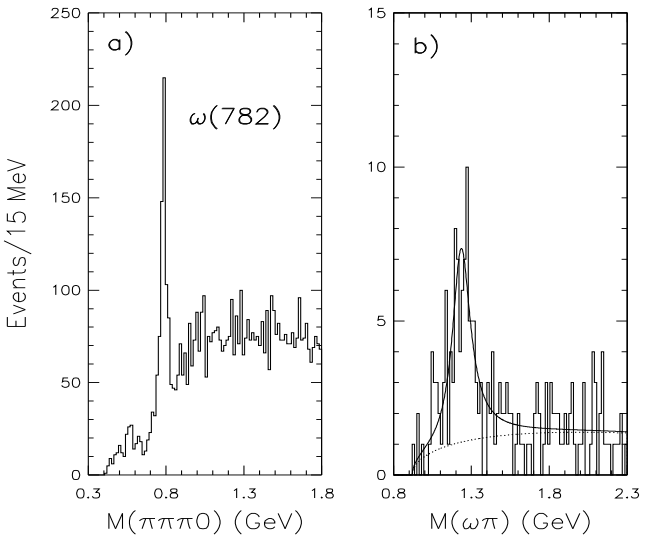

FIG. 1. The **a)** $\pi^+\pi^-\pi^0$ and **b)** $\omega\pi^\pm$ mass distributions from $\psi(2S) \to \pi^+\pi^-\pi^+\pi^-\pi^0$ events. The curve in **b)** is a fit to the b_1 resonance plus a smooth background function.

Using an acceptance determined from a Monte Carlo simulation of the experiment and a total number of $\psi(2S)$ decays in our event sample inferred from the observed number of $\psi(2S) \to \pi^+\pi^- J/\psi$ cascade events [9], we determine a $\psi(2S) \to b_1\pi$ branching fraction of [11]

$$\mathcal{B}(\psi(2S) \to b_1^\pm\pi^\mp) = (5.3 \pm 0.8 \pm 0.8) \times 10^{-4},$$

where the first error is statistical and the second is systematic and includes uncertainties associated with the shape of the background under the b_1 peak and uncertainties in the acceptance calculations. The result is higher than, but consistent with, the 14% rule expectation applied to the PDG result for the J/ψ [12].

B. $\psi(2S) \to K_1(1270)\overline{K}$ and $K_1(1400)\overline{K}$

For the $K_1\overline{K}$ decays, we select events of the type $\psi(2S) \to K^+K^-\pi^+\pi^-$ on the basis of the quality of a 4-C kinematic fit. This final state includes the dominant $K_1^\pm(1270)$ and $K_1^\pm(1400)$ decay channels. Figures 2a and b show the $\pi^+\pi^-$ and $K^\pm\pi^\mp$ invariant masses for the selected selected events, where signals for a $\rho(770)$ and a $K^*(892)$ are evident. We identify $\pi^+\pi^-$ pairs with invariant mass in the range $M_\rho \pm 150$ MeV as $\rho(770)$ candidates and $K^\pm\pi^\mp$ pairs with invariant mass in the range $M_{K^*} \pm 50$ MeV as $K^*(892)$ candidates.

The $K^\pm\rho$ mass distribution exhibits a strong enhancement near $M_{K\rho} = 1.27$ GeV, as shown in Fig. 3a. We fit the $K^\pm\rho^0$ mass distribution with a specially devised function, $f_{K\rho}$, that takes into account the distortions to the line shape caused by the restricted phase space available for the $K_1(1270) \to K\rho$ decay [13]. This plus a smooth background function that has a phase-space behaviour near threshold provide an adequate fit to the data for masses below 2.0 GeV and yields a $K_1(1270)$ signal of 53.5 ± 9.5 events.

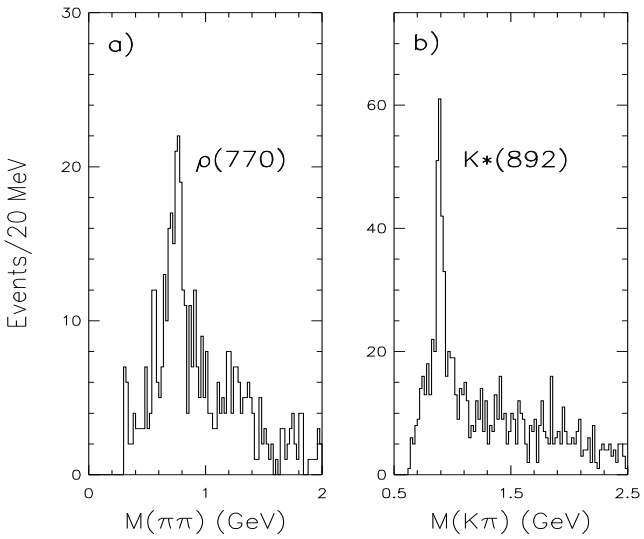

FIG. 2. The **a)** $\pi^+\pi^-$ and **b)** $K^\pm\pi^\mp$ mass distributions in the selected $\psi(2S) \to K^+K^-\pi^+\pi^-$ event sample.

In the $K^*\pi^\pm$ invariant mass distribution, shown in Fig. 3b, there is no evidence for a $K_1(1400)$ signal. Since the $K\rho$ and $K^*\pi$ selection cuts are not mutually exclusive, some feedthrough from $K_1(1270) \to K\rho$ into the $K^*\pi$ channel is expected, and seen. The smooth curve in Fig. 3b is the result of a fit using $f_{K\rho}$ for the $K_1(1270)$, an s-wave Breit Wigner with mass and width fixed at the PDG values for the $K_1(1400)$ and a smooth background shape as was used for the $K\rho$ distribution. Since the $K^*\pi$ mass distribution can be adequately fit without any $K_1(1400)$, we derive a 90% CL upper limit of 41.6 $K_1(1400) \to K^*\pi$ events.

The resulting $K_1(1270)\overline{K}$ branching ratio is

$$\mathcal{B}(\psi(2S) \to K_1^\pm(1270)K^\mp) = (10.0 \pm 1.8 \pm 1.8) \times 10^{-4},$$

and the 90% CL upper limit for $K_1(1400)\overline{K}$ mode is

$$\mathcal{B}(\psi(2S) \to K_1^\pm(1400)K^\mp) < 2.9 \times 10^{-4} \quad 90\% \text{ CL}.$$

Contrary to flavor-SU(3) expectations, the $\psi(2S) \to K_1(1400)\overline{K}$ branching fraction is smaller than that for the $K_1(1270)\overline{K}$ channel by at least a factor of three. To accommodate this with the mixing angle, a value $\theta < 30^0$ would be required.

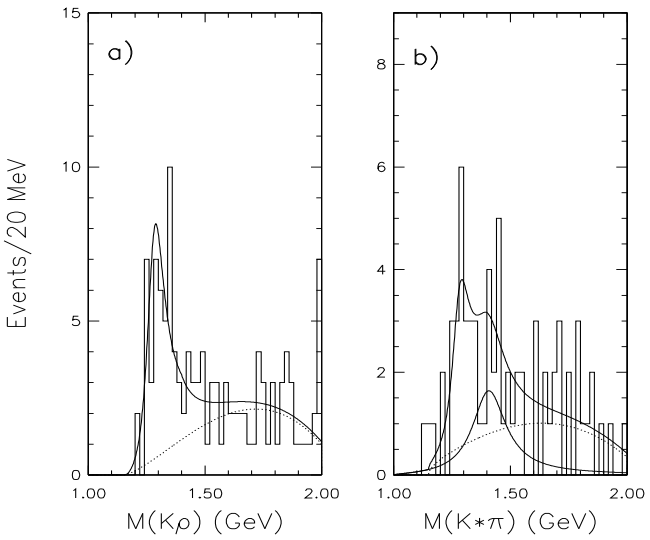

FIG. 3. The **a)** $K^{\pm}\rho^0$ and **b)** $K^*\pi^{\pm}$ mass distributions from $\psi(2S) \to K^+K^-\pi^+\pi^-$ events. Note the difference in the vertical scales. The curves are the results of the fits discussed in the text.

C. $J/\psi \to K_1(1270)\overline{K}$ and $K_1(1400)\overline{K}$

In the absence of any published results for J/ψ decays to these channels, we used the $\psi(2S) \to \pi^+\pi^- J/\psi$ cascade events in our $\psi(2S)$ data sample to make a first measurement of the branching fractions for $J/\psi \to K_1(1270)\overline{K}$ and $K_1(1400)\overline{K}$. We select events that fit a five-constraint fit to the $\psi(2S) \to \pi^+\pi^- J/\psi; J/\psi \to K^+K^-\pi^+\pi^-$ hypothesis. We use the particle species assignment that gives the best χ^2 value, and reject events where the BES particle identification system unambiguously identifies as a pion a particle that the fit assigned as a kaon. We use the same $K\rho$ and $K^*\pi$ event selection criteria that are used for the analysis of direct $\psi(2S)$ decays.

In contrast to the case for the $\psi(2S)$, the $K\rho$ mass spectrum in $J/\psi \to K^+K^-\pi^+\pi^-$ decays, shown in Fig. 4a, has little evidence for the $K_1(1270)$. Since we can find adequate fits to the spectrum with no $K_1(1270)$ signal, we use the $K_1(1270)$ signal shown in Fig. 4a to infer a 90% CL upper limit of 15.2 $K_1(1270)$ events. In further contrast to the $\psi(2S)$, the $K^{*0}\pi^{\pm}$ mass distribution for the J/ψ decays, shown in Fig. 4b, exhibits a clear $K_1(1400)$ signal; the fit to the $K^*\pi$ mass spectrum yields 59.0 ± 13.1 in the $K_1(1400)$ signal.

We determine a 90% CL upper limit for the $J/\psi \to K_1(1270)\overline{K}$ of

$$\mathcal{B}(J/\psi \to K_1^{\pm}(1270)K^{\mp}) < 2.9 \times 10^{-3} \quad 90\% \text{ CL};$$

this is more than a factor of two below the result expected from applying the 14% rule to our result for $\psi(2S)$ decays to this channel. Our result for the $J/\psi \to K_1(1400)\overline{K}$ branching fraction is

$$\mathcal{B}(J/\psi \to K_1^{\pm}(1400)K^{\mp}) = (3.8 \pm 0.8 \pm 0.5) \times 10^{-3},$$

which is above our upper limit for the $K_1(1270)\overline{K}$ mode, indicating a flavor-SU(3) violation in J/ψ decays that is opposite to that seen in $\psi(2S)$ decays. Accommodating this effect in J/ψ decays by adjusting the mixing angle would require a value of $\theta > 49^0$, in contradiction to the $\theta < 30^0$ result from $\psi(2S)$ decays.

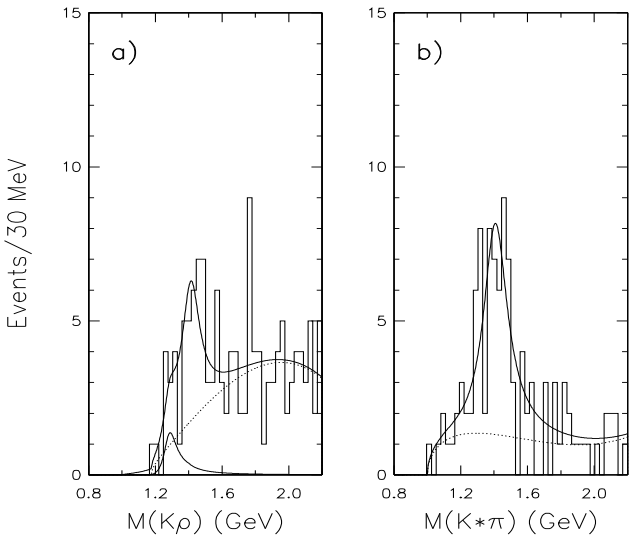

FIG. 4. The **a)** $K^{\pm}\rho^0$ and **b)** $K^{\pm}\pi^{\mp}$ mass distributions from $J/\psi \to K^+K^-\pi^+\pi^-$ decays. The curve is the result of the fit described in the text. A $K_1(1270)$ signal is not needed to get an acceptable fit to the $K^{\pm}\pi^{\mp}$ distribution.

IV. SUMMARY

We report first measurements for the $\psi(2S) \to b_1^{\pm}\pi^{\mp}$ and $K_1^{\pm}(1270)K^{\mp}$ decay branching fractions and a 90% CL upper limit for $\mathcal{B}(\psi(2S) \to K_1^{\pm}(1400)K^{\mp})$. We find that two of the AP decays are relatively strong exclusive hadron channels for the $\psi(2S)$. In addition, we report the first observation of the $J/\psi \to K_1^{\pm}(1400)K^{\mp}$ decay mode and a 90% CL upper limit for $J/\psi \to K_1^{\pm}(1270)K^{\mp}$.

The $\psi(2S) \to K_1(1270)\overline{K}$ result is the first observation of an exclusive $\psi(2S)$ two-body meson decay process that is enhanced relative to the J/ψ in the context of the 14% rule. This result as well as the lack of suppression in the $b_1\pi$ channel rule out explanations for the $\rho\pi$ puzzle that suppress all $\psi(2S)$ decays to lowest lying two-body meson final states. In addition, we observe flavor-SU(3)-violating $K_1(1270)$-$K_1(1400)$ asymmetries that have opposite characters for the $\psi(2S)$ and J/ψ. This can not be accommodated by adjustments of the singlet-triplet mixing angle.

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[10] When the change in the QCD coupling strength $\alpha_s(Q^2)$ between $Q^2 = M^2_{J/\psi}$ and $M^2_{\psi(2S)}$ is taken into account, the expectation for the given ratio is lowered to 0.12 ± 0.02.

[11] We assume that $b_1^+ \to \omega\pi^+$ branching fraction is 100%.

[12] The PDG value for $Br(J/\psi \to b_1^\pm \pi^\mp)$ is $(3.0 \pm 0.5) \times 10^{-3}$. As a check of our $\psi(2S)$ measurement, we applied the same procedures to J/ψ's from $\psi(2S) \to \pi^+\pi^- J/\psi$ cascade decays and find a result that agrees within errors with the PDG value.

[13] The function used to fit the $K_1(1270)$ is a convolution of an s-wave Breit Wigner function with mass and width fixed at the PDG values for the $K_1(1270)$ with a p-wave ρ meson Breit Wigner. The requirement that the $\pi^+\pi^-$ mass is within ± 150 MeV of the $\rho(770)$ is set in the limits of the convolution integral.