Measurement of interference between electromagnetic and strong amplitudes in $\psi(2S)$ decays to two pseudoscalar mesons

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Using a sample of 3.08×10^6 $\psi(2S)$ decays collected at $\sqrt{s} = 3.686$ GeV with the CLEO detector at the Cornell Electron Storage Ring, we have measured the branching fractions for $\psi(2S)$ decays to pseudoscalar pairs $\pi^+\pi^-$, K^+K^- and $K_S^0 K_L^0$. We obtain $\mathcal{B}(\psi(2S) \to \pi^+\pi^-) < 2.1 \times 10^{-5}$ (90% C.L.), $\mathcal{B}(\psi(2S) \to K^+K^-) = (6.3 \pm 0.6(\text{stat}) \pm 0.3(\text{syst})) \times 10^{-5}$, and $\mathcal{B}(\psi(2S) \to K_S^0 K_L^0) = (5.8 \pm 0.8(\text{stat}) \pm 0.4(\text{syst})) \times 10^{-5}$. The branching fractions allow extraction of the relative phase $\Delta = (95 \pm 15)°$ and strength ratio $R = (2.5 \pm 0.4)$ of the three-gluon and one-photon amplitudes for these modes.

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The decay of narrow vector states of charmonium, J/ψ and $\psi(2S)$, into states of light quarks can proceed via $c\bar{c}$ annihilation into a virtual photon or three gluons. The decays of J/ψ to pseudoscalar pairs (PP) have been analyzed by several authors [1–4], and it has been determined that the decay $J/\psi \to \pi^+\pi^-$ proceeds dominantly through one photon, the decay $J/\psi \to K_S^0 K_L^0$ proceeds dominantly through three gluons, and the decay $J/\psi \to K^+K^-$ may proceed through both one-photon and three-gluon channels, with a phase difference of nearly 90° between the two amplitudes. Under the simplifying assumption that the SU(3) breaking correction to the one-photon annihilation amplitude is negligibly small, Suzuki [1] has determined the relative phase angle to be $\Delta(J/\psi) = (89.6 \pm 9.9)°$ and Rosner [2] has confirmed it with the result $\Delta(J/\psi) = (89 \pm 10)°$. The branching fractions for the corresponding decays of $\psi(2S)$ were not available to either Gerard and Weyers [3] or Suzuki [4], but both of them speculated that $\psi(2S)$ decays would have characteristics similar to those of J/ψ decays. In a recent attempt, Yuan *et al.* [5] used the unpublished BES results [6] for $\mathcal{B}_{\pi^+\pi^-} \equiv \mathcal{B}(\psi(2S) \to \pi^+\pi^-)$ and $\mathcal{B}_{K^+K^-} \equiv \mathcal{B}(\psi(2S) \to K^+K^-)$ to study the interference between electromagnetic and strong amplitudes but were not able to obtain an estimate of their relative phase and magnitude in the absence of a measurement of the branching fraction for the decay $\psi(2S) \to K_S^0 K_L^0$. A subsequent measurement by BES of $\mathcal{B}_{K_S^0 K_L^0} \equiv \mathcal{B}(\psi(2S) \to K_S^0 K_L^0)$ [7], together with the older BES results for the other two decays, has led to $\Delta(\psi(2S)) = (-82 \pm 29)°$ or $(+121 \pm 27)°$.

In this paper, we report on the results of CLEO measurements of all three branching fractions. We have an improved K^+K^- branching fraction measurement and the $K_S^0 K_L^0$ mode is essentially background free and consistent with the earlier BES measurement. Using our measurements, we determine the ratio of the amplitudes of $\psi(2S) \to$ PP decays via a photon and three gluons and the phase difference between the two. We also report on the ratios of $\mathcal{B}(\psi(2S))/\mathcal{B}(J/\psi)$ for the three decays to test the "12%" rule [8].

The data used in this analysis were collected at the CESR e^+e^- storage ring, which has been reconfigured to run in the charm meson region by insertion of wiggler magnets [9]. Our analysis is based on 3.08×10^6 $\psi(2S)$ decays, which corresponds to a total integrated luminosity of 5.63 pb^{-1}, produced at the peak cross section at $\sqrt{s} = 3.686$ GeV. Approximately half of these data (2.74 pb^{-1}) were taken with the CLEO III detector configuration [10], while the remainder (2.89 pb^{-1}) of the $\psi(2S)$ data, together with 20.7 pb^{-1} of off-resonance data taken at $\sqrt{s} = 3.671$ GeV, were collected with the reconfigured CLEO-c detector [9]. Both detector configurations are cylindrically symmetric and provide 93% coverage of solid angle for charged and neutral particle identification. The detector components important for this analysis are the main drift

chamber (DR), the Ring-Imaging CHerenkov detector (RICH), and the CsI crystal calorimeter (CC), all of which are common to both detector configurations.

The properties of the PP modes are studied by generating Monte Carlo events (EVTGEN event generator [11]) using simulations of each of the two detector configurations and for each of the three decay modes using a GEANT-based [12] detector modeling program. For all three modes, events are simulated with $\sin^2\theta$ angular distributions, where θ is the angle between the decay product and the positron beam in the center-of-mass system, as is expected for a vector resonance decaying into two pseudoscalar mesons.

The events for each of the charged PP decay modes are required to have two charged particles and zero net charge. In the case of the neutral PP mode, K_S^0 candidates are formed from a pair of two charged tracks which are constrained to come from a common vertex, are consistent with the pion hypothesis, and possess an invariant mass within 10 MeV($\approx 3.2\sigma$) of the nominal K_S^0 mass. The charged particles in the $\pi^+\pi^-$, K^+K^-, and $K_S^0 K_L^0$ (i.e., the $\pi^+\pi^-$ daughters of the K_S^0) decay modes are required to have $|\cos\theta| < 0.75$, <0.93 and <0.93, respectively. In the case of the $\pi^+\pi^-$ mode, the additional requirement of an associated shower in the CC is imposed. Furthermore, each of the charged particles is required to satisfy standard criteria for track quality and distance of closest approach to the interaction point. For the neutral PP mode the latter requirement is reversed and a displaced secondary K_S^0 vertex (intersection of the $\pi^+\pi^-$ daughters) condition of >5 mm is imposed.

We require momentum conservation in the reconstructed charged PP events by demanding the magnitude of the vector sum of the total momentum in an event, $|\Sigma\vec{p}|/E_{\text{beam}}$, to be <0.04 for the K^+K^- mode and <0.054 for the $\pi^+\pi^-$ mode. This eliminates background via $\pi\pi J/\psi$ or $\gamma\chi_{cJ}$ ($J = 0$, 1 and 2) decays of the $\psi(2S)$.

To optimize the discrimination between p, K, π, μ and e, we combine the particle identification information obtained from the specific ionization (dE/dx) measured in the DR with that obtained from the RICH detector to form a joint χ^2 function. For dE/dx, we form a quantity S_i ($i = p$, K, π, μ, and e), which is the difference between the measured and expected dE/dx for that hypothesis, normalized to its standard deviation. The information from the RICH is given in the form of a likelihood function, $-2\log L$. The joint χ^2 function is $\Delta\chi^2(i - j) = -2\log L_i + 2\log L_j + S_i^2 - S_j^2$. The more negative $\Delta\chi^2$, the higher the likelihood that the particle is of type i compared to type j [9]. The requirement on these quantities varies in value from mode to mode depending upon background considerations. For kaons in the K^+K^- decay mode for 3σ separation we require $\Delta\chi^2(K - p) < -9$ and $\Delta\chi^2(K - \pi) < -9$. For pions in the $\pi^+\pi^-$ decay mode we require looser particle identification criteria

$\Delta\chi^2(\pi - e) < 0$ and $\Delta\chi^2(\pi - K) < 0$. In the case of $\pi^+\pi^-$ daughters of the K_S^0 in the neutral $K_S^0 K_L^0$ mode, we impose similar criteria $\Delta\chi^2(\pi - K) < 0$ and $\Delta\chi^2(\pi - p) < 0$.

QED processes ($e^+e^- \to \gamma\gamma$ and l^+l^-, $l = e, \mu$) are possible background sources in these final states. To combat the charged dilepton contamination, in the case of the K^+K^- mode, we require $\Delta\chi^2(K - e/\mu) < -9$ for the charged tracks. For the $K_S^0 K_L^0$ mode, we reject as an electron any daughter pion track with the ratio of CC energy E_{CC} to track momentum p of $0.92 < E_{\text{CC}}/p < 1.05$ and $\Delta\chi^2(\pi - e) < 0$. In order to suppress the more severe e^+e^- background events in the $\pi^+\pi^-$ decay mode, we require $E_{\text{CC}}/p < 0.85$ for pion candidate tracks. Rejecting $\mu^+\mu^-$ background events from the $\pi^+\pi^-$ sample requires additional measures, which are determined by studying muon tracks from a $e^+e^- \to \mu^+\mu^-$ simulation sample and by studying pions of appropriate momenta ($\sim$ 1.83 GeV/c) in the existing CLEO sample of inclusive $D^0 \to K^-\pi^+$ data taken at $\sqrt{s} = 10.58$ GeV. The optimization criterion is that each pion must deposit $E_{\text{CC}} >$ 0.42 GeV. For the $K_S^0 K_L^0$ mode, we do not attempt to reconstruct the K_L^0. In order to reject most of the anticipated backgrounds (discussed later), we reject events with neutral particles other than a K_L^0 accompanying the reconstructed K_S^0 in an event. We require the energy of the shower associated with neutrals, and closest to the inferred K_L^0 direction (obtained from the 4-momentum of the beam and the reconstructed K_S^0), to be less than 1.5 GeV. We define a cone of 0.35 radians around the K_L^0 direction and require that of all showers associated with neutrals outside (inside) this cone, there be none (at most one) with $E >$ 100 MeV, and that the sum of all showers outside this cone does not exceed 300 MeV. We also have an explicit π^0 veto for even better rejection of events which have one or more π^0 mesons from neutral sources of backgrounds.

For each charged PP candidate event, we calculate the scaled visible energy, $E_{\text{vis}}/\sqrt{s}$, where E_{vis} is the energy reconstructed in an event and $\sqrt{s}$ is the center-of-mass energy. For each $K_S^0 K_L^0$ candidate event, we calculate the scaled K_S^0 energy, $E_{K_S^0}/E_{\text{beam}}$, where $E_{K_S^0}$ is the measured K_S^0 energy and E_{beam} is the beam energy. We define our signal region to be $0.98 < E_{\text{vis}}/\sqrt{s}$ (or $E_{K_S^0}/E_{\text{beam}}$) < 1.02,

and two sideband regions of 0.94–0.98 and 1.02–1.06, as representative of the combinatorial background.

We study the data sample taken at $\sqrt{s} = 3.671$ GeV (continuum) to check for possible nonresonant contributions in our $\psi(2S)$ signals. This is found to be nonnegligible for the charged PP decay modes as shown in Table I. We multiply the yield from the continuum data by a scaling factor f_s, which is calculated taking into account the luminosity ratio (5.63/20.7 = 0.272), a $1/s^3$ correction for mesons, and the values of the efficiencies in the CLEO III and CLEO-c detector configurations before subtracting it from the $\psi(2S)$ yields. The scale factors are $f_s = 0.265$, 0.261 and 0.250 for the $\pi^+\pi^-$, K^+K^- and $K_S^0 K_L^0$ final states, respectively.

Figure 1 shows the scaled energy distribution for each of the decay modes with the points showing the data, the solid histogram showing the simulation results, and the dashed histogram showing the scaled nonresonant contribution. In all modes clear signals are seen, with widths consistent with those expected from simulation studies. The $\pi^+\pi^-$ mode, shown in Fig. 1(a), is statistics limited and has no combinatorial background, but there is a large background contribution from nonresonant e^+e^- annihilation events. Figure 1(b) for the K^+K^- mode shows an excess due to misidentified dilepton pairs around $E_{\text{vis}}/\sqrt{s} = 1.03$, and some non-negligible nonresonant background is also present. In the $K_S^0 K_L^0$ mode, shown in Fig. 1(c), the background is asymmetric. The low sideband region around $E_{K_S^0}/E_{\text{beam}} = 0.96$ is contaminated from known hadronic sources such as $K^{*0}(892)\bar{K}^0 +$ c.c. (both the $\psi(2S)$ [15] and the continuum below the resonance can produce this final state), and the $K_S^0 K_S^0$ final state which is possible through radiative transitions to the $\chi_{c0,2}$ [13]. We account for possible background contamination inside the signal region by a systematic uncertainty component obtained from simulation studies.

The signal yield N_S is obtained by subtracting from the observed yield $S_{\psi(2S)}$, the QED (scaled sideband) contribution N_{QED}, and the scaled contribution $f_s \cdot N_{\text{cont}}$ from the observed yield in the continuum (minus the QED contribution in it), N_{cont}: $N_S = S_{\psi(2S)} - N_{\text{QED}} - f_s \cdot N_{\text{cont}}$. A possible contamination from the $\psi(2S)$ tail in the continuum yield is found to be negligibly small in all

TABLE I. Experimental results for $\psi(2S)$ decays into pairs of pseudoscalar mesons. The first errors are statistical and the second errors are systematic. The last column shows the "Q" value which is the ratio of $\mathcal{B}(\psi(2S) \to PP)$ to $\mathcal{B}(J/\psi \to PP)$ [13,14] with statistical and systematic uncertainties added in quadrature.

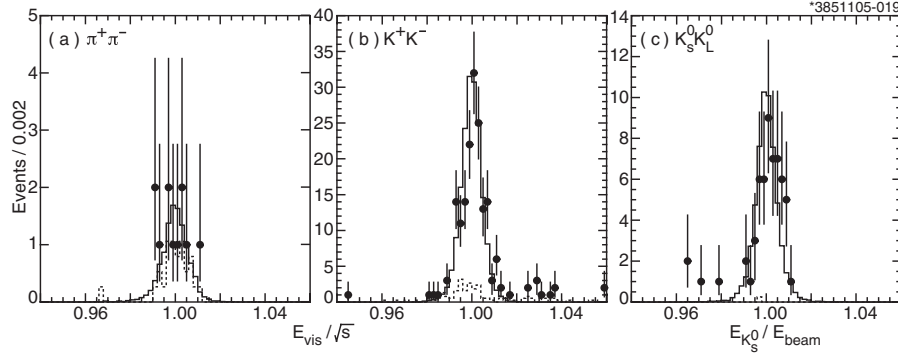| Modes	$S_{\psi(2S)}$	N_{QED}	$f_s \cdot N_{\text{cont}}$	N_S	$\epsilon(\%)$	$\mathcal{B}(10^{-5})$	$Q(\%)$
$\pi^+\pi^-$	11	<0.1	6.8	4.2	16.7	$0.8 \pm 0.8 \pm 0.2$	5.4 ± 5.6
						<2.1(90%C.L.)	<14.6(90%C.L.)
K^+K^-	163	6.0	17.8	139.2	71.7	$6.3 \pm 0.6 \pm 0.3$	26.6 ± 4.5
$K_S^0 K_L^0$	53	—	0.3	52.7	42.8	$5.8 \pm 0.8 \pm 0.4$	32.2 ± 5.2

FIG. 1. Scaled energy ($E_{\mathrm{vis}}/\sqrt{s}$) distributions for the $\psi(2S) \rightarrow$ (a) $\pi^+\pi^-$ and (b) K^+K^- decay modes and the scaled K_s^0 energy ($E_{K_S^0}/E_{\mathrm{beam}}$) distribution for the $\psi(2S) \rightarrow$ (c) $K_L K_S$ decay mode. Signal data, signal simulations, and scaled nonresonant data are shown as points, solid histograms, and dashed histograms, respectively. The signal simulations are normalized to the number of observed events in their respective signal regions.

modes. In Table I the observed yields and backgrounds are listed, as are the efficiencies calculated using the luminosity weighted average from the simulation studies for the CLEO III and CLEO-c detectors. It should be noted that, since hadronic showers in the calorimeter are not precisely modeled, the total efficiency for the $\pi^+\pi^-$ mode is determined from the $\psi(2S) \rightarrow \pi^+\pi^-$ simulations with the exception of the E_{CC} criterion, which is the average track efficiency from the simulation and inclusive D^0 data samples. The branching fractions are obtained as $N_S/[N(\psi(2S)) \cdot \epsilon]$, with $N(\psi(2S)) = 3.08 \times 10^6$ and ϵ denoting the detection efficiency for the respective modes. For $\pi^+\pi^-$ both the measured value and the corresponding 90% confidence upper limit are listed. For $K_S^0 K_L^0$ the listed value is obtained using $\mathcal{B}(K_S^0 \rightarrow \pi^+\pi^-) = (68.95 \pm 0.14)\%$ [13]. The entries for Q are obtained using the literature [13,14] values for J/ψ branching fractions with statistical and systematic errors combined in quadrature.

We evaluate the following systematic uncertainties to our measured branching fractions for the charged (neutral) PP modes: 3.0% uncertainty on the number of $\psi(2S)$ decays; 1.0% (2.0%) uncertainty in the simulation of our hardware trigger; 1.0% (1.4%) uncertainty in the reconstruction of each charged track; 1.0% and 2.7% (0.6%) uncertainties for kaon and pion identification. Uncertainties in the $\pi^+\pi^-$, K^+K^-, and $K_S^0 K_L^0$ modes arising due to background subtraction procedures are 0.2%, 1.4%, and 3.8%; and those due to simulation statis-

tics are 1.3%, 1.6%, and 0.4%, respectively. Additional uncertainties in the $\pi^+\pi^-$ mode from the $E_{\mathrm{vis}}/\sqrt{s}$, $|\Sigma\vec{p}|/E_{\mathrm{beam}}$, and E_{CC} criteria are conservatively determined to be 1.4%, 24.3%, and 12.1%, respectively. The uncertainties in the $|\Sigma\vec{p}|/E_{\mathrm{beam}}$ and E_{CC} criteria arise from statistical fluctuations not accounted for in the $\pi^+\pi^-$ detection efficiency. In the $K_S^0 K_L^0$ mode, additional uncertainties arise due to K_L^0 selection (3.7%), K_S^0 finding (3.0%), and the $\mathcal{B}(K_S^0 \rightarrow \pi^+\pi^-)$ [13] (0.1%). After combining all contributions in quadrature, the total systematic uncertainties for the $\pi^+\pi^-$, K^+K^-, and $K_S^0 K_L^0$ final states are 28.0%, 4.7% and 7.3%, respectively.

The results in Table I show that the statistical errors are larger than the systematic errors, particularly for the $\pi^+\pi^-$ mode. The branching fractions $\mathcal{B}_{K^+K^-}$ and $\mathcal{B}_{K_S^0 K_L^0}$ are larger than predicted by the "12% rule".

In Table II we summarize the branching ratios for the three PP decays from the literature, from our measurements, and the world averages. We also list the resulting ratios of the strong/electromagnetic amplitudes and the phase differences between them. The procedure for determining these is described in the following.

It was noted by both Suzuki [1] and Rosner [2] that the available data for J/ψ were not precise enough to enable one to take into account the effects of the possible SU(3) breaking correction to the one-photon annihilation amplitude. Neither was it possible to consider the effects of the resonance interference with the continuum. For $\psi(2S)$

TABLE II. Branching fractions used for determination of strong/EM interference parameters. The statistical and systematic errors have been combined in quadrature.

	DASP	BES	CLEO	World Avg.
$\mathcal{B}_{\pi^+\pi^-}(\times 10^{-5})$	8 ± 5[16]	0.84 ± 0.65[6]	0.8 ± 0.8	0.9 ± 0.5
$\mathcal{B}_{K^+K^-}(\times 10^{-5})$	10 ± 7[16]	6.1 ± 2.1[6]	6.3 ± 0.7	6.3 ± 0.7
$\mathcal{B}_{K_S^0 K_L^0}(\times 10^{-5})$	—	5.24 ± 0.67[7]	5.8 ± 0.9	5.4 ± 0.6
$R(\psi(2S))$	—	$2.6^{+0.9}_{-1.4}$	$2.8^{+1.2}_{-2.8}$	$2.6^{+0.7}_{-0.9}$
$\Delta(\psi(2S))$	—	$(89 \pm 35)°$	$(93 \pm 20)°$	$(89 \pm 14)°$

decays the statistical precision is even poorer. We are therefore obliged to also forego the consideration of the SU(3) breaking and $\psi(2S)$-continuum interference. With these assumptions, following Rosner [2], we obtain the phase difference and ratio of amplitudes between the strong three-gluon, $A(ggg)$, and electromagnetic, $A(\gamma)$, decays as follows:

$$R(\psi(2S)) = \frac{A(ggg)}{A(\gamma)} = \sqrt{\frac{\mathcal{B}_{K^0_S K^0_L}}{\rho \mathcal{B}_{\pi^+ \pi^-}}}, \qquad (1)$$

$$\Delta(\psi(2S)) = \cos^{-1}\left(\frac{\mathcal{B}_{K^+ K^-} - \mathcal{B}_{K^0_S K^0_L} - \rho \mathcal{B}_{\pi^+ \pi^-}}{2\sqrt{\mathcal{B}_{K^0_S K^0_L} \cdot \rho \mathcal{B}_{\pi^+ \pi^-}}}\right), \quad (2)$$

where the phase space ratio $\rho = (p_K/p_\pi)^3 = 0.902$.

The results in Table II are further improved if the CLEO result for $\mathcal{B}_{\pi^+ \pi^-}$ from direct counting is replaced by that obtained from the recent CLEO measurement of the charged pion form factor $|F_\pi(\sqrt{s} = 3.671 \text{ GeV})| = 0.075 \pm 0.009$ [17]. Under the assumption that the $\psi(2S)$ decay to $\pi^+ \pi^-$ is purely electromagnetic, it can be shown that [18]

$$\mathcal{B}_{\pi^+ \pi^-} = 2\mathcal{B}_{e^+ e^-}\left(\frac{p_\pi}{M_{\psi(2S)}}\right)^3 |F_\pi(M^2_{\psi(2S)})|^2. \qquad (3)$$

Using this relation we obtain $\mathcal{B}_{\pi^+ \pi^-} = (1.04 \pm 0.23) \times 10^{-5}$. With this value $R(\text{CLEO}) = 2.5 \pm 0.4$ and $\Delta(\text{CLEO}) = (95 \pm 15)°$, and $R(\text{WorldAvg.}) = 2.4 \pm 0.4$ and $\Delta(\text{WorldAvg.}) = (90 \pm 12)°$.

As a by-product of this work, from the one $K^0_S K^0_L$ event observed in the continuum data, we obtain the 90% C.L. for the Born cross section for $e^+ e^-$ annihilation to $K^0_S K^0_L$ to be $\sigma_0(e^+ e^- \rightarrow K^0_S K^0_L) < 0.74$ pb at $\sqrt{s} = 3.671$ GeV. This cross section includes the radiative corrections from the $K^+ K^-$ analysis in Ref. [17]. Using the relation [19]

$$\sigma_0(s) = \frac{\pi\alpha^2}{3s}\beta^3_{K^0}|F_{K^0}(s)|^2, \qquad (4)$$

where α is the fine-structure constant, β_{K^0} is the K^0_S velocity in the laboratory system, and $|F_{K^0}(s)|$ is the neutral kaon electromagnetic form factor, we obtain $|F_{K^0}(s = 13.48 \text{ GeV}^2)| < 0.023$ at 90% C.L. including systematic uncertainties obtained for the $K^0_S K^0_L$ mode. Previous measurements of this form factor were limited to $s < 4.5$ GeV^2 [20].

In conclusion, we have analyzed CLEO III and CLEO-c $\psi(2S)$ data and have presented new measurements of the branching fractions into $\pi^+ \pi^-$, $K^+ K^-$, and $K^0_S K^0_L$ final states. This has allowed the determination of parameters of the interference between the amplitudes for the strong and electromagnetic decays of $\psi(2S)$ into pseudoscalar pairs. In particular, the phase difference between the two amplitudes is found to be nearly 90° [3,4].

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