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Measurement of Interference between Electromagnetic and Strong Amplitudes in $\psi(2S)$ Decays to Two Pseudoscalar Mesons

S. Dobbs,[1] Z. Metreveli,[1] K. K. Seth,[1] A. Tomaradze,[1] P. Zweber,[1] J. Ernst,[2] H. Severini,[3] S. A. Dytman,[4] W. Love,[4] S. Mehrabyan,[4] V. Savinov,[4] O. Aquines,[5] Z. Li,[5] A. Lopez,[5] H. Mendez,[5] J. Ramirez,[5] G. S. Huang,[6] D. H. Miller,[6] V. Pavlunin,[6] B. Sanghi,[6] I. P. J. Shipsey,[6] B. Xin,[6] G. S. Adams,[7] M. Anderson,[7] J. P. Cummings,[7] I. Danko,[7] J. Napolitano,[7] Q. He,[8] J. Insler,[8] H. Muramatsu,[8] C. S. Park,[8] E. H. Thorndike,[8] T. E. Coan,[9] Y. S. Gao,[9] F. Liu,[9] R. Stroynowski,[9] M. Artuso,[10] S. Blusk,[10] J. Butt,[10] J. Li,[10] N. Menaa,[10] R. Mountain,[10] S. Nisar,[10] K. Randrianarivony,[10] R. Redjimi,[10] R. Sia,[10] T. Skwarnicki,[10] S. Stone,[10] J. C. Wang,[10] K. Zhang,[10] S. E. Csorna,[11] G. Bonvicini,[12] D. Cinabro,[12] M. Dubrovin,[12] A. Lincoln,[12] D. M. Asner,[13] K. W. Edwards,[13] R. A. Briere,[14] I. Brock,[14,*] J. Chen,[14] T. Ferguson,[14] G. Tatishvili,[14] H. Vogel,[14] M. E. Watkins,[14] J. L. Rosner,[15] N. E. Adam,[16] J. P. Alexander,[16] K. Berkelman,[16] D. G. Cassel,[16] J. E. Duboscq,[16] K. M. Ecklund,[16] R. Ehrlich,[16] L. Fields,[16] R. S. Galik,[16] L. Gibbons,[16] R. Gray,[16] S. W. Gray,[16] D. L. Hartill,[16] B. K. Heltsley,[16] D. Hertz,[16] C. D. Jones,[16] J. Kandaswamy,[16] D. L. Kreinick,[16] V. E. Kuznetsov,[16] H. Mahlke-Krüger,[16] T. O. Meyer,[16] P. U. E. Onyisi,[16] J. R. Patterson,[16] D. Peterson,[16] E. A. Phillips,[16] J. Pivarski,[16] D. Riley,[16] A. Ryd,[16] A. J. Sadoff,[16] H. Schwarthoff,[16] X. Shi,[16] S. Stroiney,[16] W. M. Sun,[16] T. Wilksen,[16] M. Weinberger,[16] S. B. Athar,[17] P. Avery,[17] L. Breva-Newell,[17] R. Patel,[17] V. Potlia,[17] H. Stoeck,[17] J. Yelton,[17] P. Rubin,[18] C. Cawlfield,[19] B. I. Eisenstein,[19] I. Karliner,[19] D. Kim,[19] N. Lowrey,[19] P. Naik,[19] C. Sedlack,[19] M. Selen,[19] E. J. White,[19] J. Wiss,[19] M. R. Shepherd,[20] D. Besson,[21] T. K. Pedlar,[22] D. Cronin-Hennessy,[23] K. Y. Gao,[23] D. T. Gong,[23] J. Hietala,[23] Y. Kubota,[23] T. Klein,[23] B. W. Lang,[23] R. Poling,[23] A. W. Scott,[23] and A. Smith[23]

(CLEO Collaboration)

[1]*Northwestern University, Evanston, Illinois 60208*
[2]*State University of New York at Albany, Albany, New York 12222*
[3]*University of Oklahoma, Norman, Oklahoma 73019*
[4]*University of Pittsburgh, Pittsburgh, Pennsylvania 15260*
[5]*University of Puerto Rico, Mayaguez, Puerto Rico 00681*
[6]*Purdue University, West Lafayette, Indiana 47907*
[7]*Rensselaer Polytechnic Institute, Troy, New York 12180*
[8]*University of Rochester, Rochester, New York 14627*
[9]*Southern Methodist University, Dallas, Texas 75275*
[10]*Syracuse University, Syracuse, New York 13244*
[11]*Vanderbilt University, Nashville, Tennessee 37235*
[12]*Wayne State University, Detroit, Michigan 48202*
[13]*Carleton University, Ottawa, Ontario, Canada K1S 5B6*
[14]*Carnegie Mellon University, Pittsburgh, Pennsylvania 15213*
[15]*Enrico Fermi Institute, University of Chicago, Chicago, Illinois 60637*
[16]*Cornell University, Ithaca, New York 14853*
[17]*University of Florida, Gainesville, Florida 32611*

[18] George Mason University, Fairfax, Virginia 22030
[19] University of Illinois, Urbana-Champaign, Illinois 61801
[20] Indiana University, Bloomington, Indiana 47405
[21] University of Kansas, Lawrence, Kansas 66045
[22] Luther College, Decorah, Iowa 52101
[23] University of Minnesota, Minneapolis, Minnesota 55455
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Abstract

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 $K^0_S K^0_L$. 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 $\mathcal{B}(\psi(2S) \to K^0_S K^0_L) = (5.8 \pm 0.8(\text{stat}) \pm 0.4(\text{syst})) \times 10^{-5}$. The branching fractions allow extraction of the relative phase $\Delta = (95 \pm 15)^\circ$ and strength ratio $R = (2.5 \pm 0.4)$ of the three-gluon and one-photon amplitudes for these modes.

*Current address: Universität Bonn, Nussallee 12, D-53115 Bonn

The decay of narrow vector states of charmonium, J/ψ and $\psi(2S)$, into states of light quarks can proceed via $c\overline{c}$ annihilation into a virtual photon or three gluons. The decays of J/ψ to pseudoscalar pairs (PP) have been analysed 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 $J/\psi \to K^0_S K^0_L$ 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 $\Delta(J/\psi) = (89.6 \pm 9.9)^\circ$ and Rosner [2] has confirmed it with the result $\Delta(J/\psi) = (89 \pm 10)^\circ$. The branching fractions for the corresponding decays of $\psi(2S)$ were not available to either Gerard and Weyers [3] or Suzuki [4] and both of them have speculated that although it may be naively expected that $\psi(2S)$ decays would have the same characteristics as J/ψ, it is possible that $\psi(2S)$ decays differ from those of J/ψ in important ways. In particular, the available phase information obtained from $\psi(2S)$ decays to vector-pseudoscalar (VP) modes could not rule out the possibility that the phase is near 180° as suggested in Ref. [4]. In a recent attempt, Yuan *et al.* [5] used the unpublished BES results 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 $\psi(2S) \to K^0_S K^0_L$. A subsequent measurement by BES of $\mathcal{B}_{K^0_S K^0_L} \equiv \mathcal{B}(\psi(2S) \to K^0_S K^0_L)$ [6], together with the older BES results for the other two decays, has led to $\Delta(\psi(2S)) = (-82 \pm 29)^\circ$ or $(+121 \pm 27)^\circ$.

In this Letter, we report on the results of CLEO measurements of all the three branching fractions. We have an improved K^+K^- branching fraction measurement and the $K^0_S K^0_L$ 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 [7].

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 [8]. Our analysis is based on 3.08×10^6 $\psi(2S)$ decays, which corresponds to a total integrated luminosity of 5.63 pb^{-1}. Approximately half of these data (2.74 pb^{-1}) were taken with the CLEO III detector configuration [9], 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 [8]. Both detector configurations are cylindrically symmetric and provide 93% coverage of solid angle for charged and neutral particle indentification. 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 [10]) using simulations of each of the two detector configurations and for each of the three decay modes using a GEANT-based [11] 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^0_S 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^0_S mass. The charged particles in the $\pi^+\pi^-$, K^+K^-, and $K^0_SK^0_L$ (i.e., the $\pi^+\pi^-$ daughters of the K^0_S) 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^0_S 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 vector sum of the total momentum in an event, $|\Sigma\vec{\mathbf{p}}|/E_{\rm beam}$, 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 $\gamma\chi_{\rm cJ}$ ($J = 0$, 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 ($i = p, K, \pi, \mu,$ 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. 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^0_S in the neutral $K^0_SK^0_L$ 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^-) are possible background sources in these final states. To combat the charged di-lepton contamination, in the case of the K^+K^- mode, we require $\Delta\chi^2(K - e/\mu) < -9$ for the charged tracks. For the $K^0_SK^0_L$ mode, we reject as an electron any daughter pion track with the ratio of CC energy $E_{\rm CC}$ to track momentum of p $0.92 < E_{\rm CC}/p < 1.05$ and $\Delta\chi^2(\pi - e) < 0$. In order to suppress the more severe l^+l^- background events in the $\pi^+\pi^-$ decay mode, it is required that the accepted events have $E_{\rm CC}/p < 0.85$ for each candidate pion track. Rejecting $\mu^+\mu^-$ background events from the $\pi^+\pi^-$ sample requires additional measures, which are determined by studying μ tracks from a $e^+e^- \to \mu^+\mu^-$ simulation sample and by studying pions of appropriate momenta (~ 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 criteria which emerge from these studies are that pions must deposit $E_{\rm CC} > 0.42$ GeV, and the average efficiency from simulations and data pion track samples is applied for each track. For the $K^0_SK^0_L$ mode, we do not attempt to reconstruct the K^0_L, and so cannot reconstruct the complete event. In order to reject most of the anticipated backgrounds (discussed later), we designed the following selection criteria to reject events with neutral particles other than a K^0_L accompanying the reconstructed K^0_S in an event. We require the energy of the shower associated with neutrals, and closest to the inferred K^0_L direction (obtained from the 4-momentum of the beam and the reconstructed K^0_S), to be less than 1.5 GeV. We define a cone of 0.35 radians around the K^0_L direction and require that of all showers associated with neutrals outside (inside) this cone, there be none

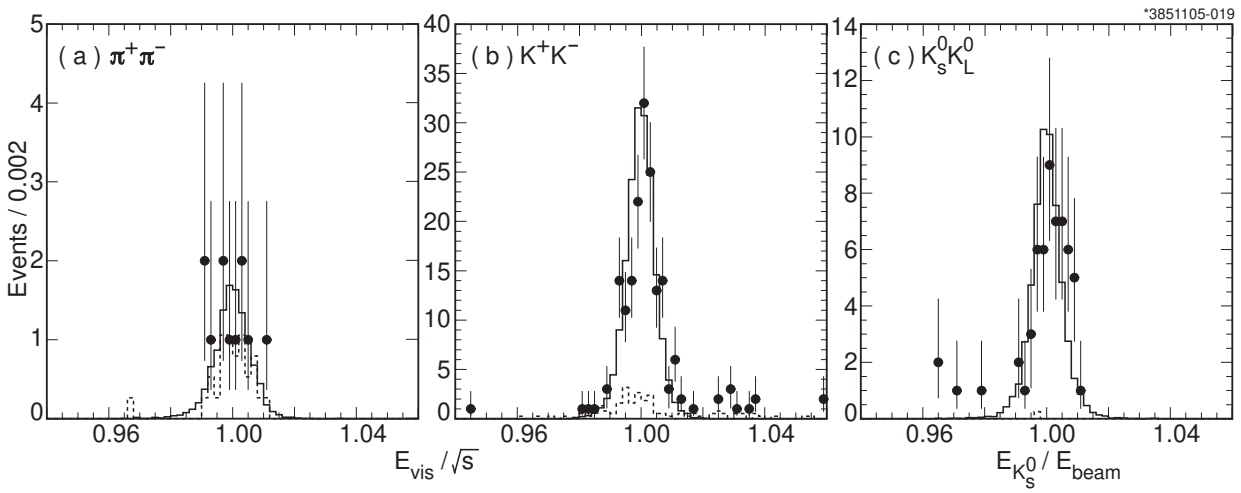

FIG. 1: Scaled energy ($E_{\rm vis}/\sqrt{s}$) distributions for the $\psi(2S)$ → (a) $\pi^+\pi^-$ and (b) K^+K^- decay modes and the scaled K^0_s energy ($E_{K^0_S}/E_{\rm beam}$) distribution for the $\psi(2S)$ → (c) K_LK_S decay mode. Signal data, signal simulations, and scaled non-resonant data are 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.

(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. Simulation studies show that after these cuts, there is minimal QED background contamination in the $K^0_SK^0_L$ final state.

For each charged PP candidate event, we calculate the scaled visible energy, $E_{\rm vis}/\sqrt{s}$, where $E_{\rm vis}$ is the energy reconstructed in an event and $\sqrt{s}$ is the center-of-mass energy. For each $K^0_SK^0_L$ candidate event, we calculate the scaled K^0_S energy, $E_{K^0_S}/E_{\rm beam}$, where $E_{K^0_S}$ is the measured K^0_S energy and $E_{\rm beam}$ is the beam energy. We define our signal region to be $0.98 < E_{\rm vis}/\sqrt{s}$ (or $E_{K^0_S}/E_{\rm beam}$) < 1.02, and two sideband regions of 0.94-0.98 and 1.02-1.06, as representative of the combinatorial background.

We also study the data sample taken at $\sqrt{s} = 3.671$ GeV (continuum) to check for possible non-resonant contributions in our $\psi(2S)$ signals. This is found to be non-negligible for the charged PP decay modes as shown in Table I. We multiply the yield from the continuum data by a scaling factor 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 $K^0_SK^0_L$ 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 non-resonant contribution. In all modes clear signals are seen, with widths consistent with those expected from simulation studies. The $\pi^+\pi^-$ mode, shown in Figure 1(a), is statistics limited and has no combinatorial background, but there is a large background contribution from non-resonant e^+e^- annihilation events. Figure 1(b) for the K^+K^- mode shows an excess due to mis-identified dilepton pairs around $E_{\rm vis}/\sqrt{s} = 1.03$

(high sideband region), and some non-negligible non-resonant background is also present. In the $K^0_S K^0_L$ mode, shown in Figure 1(c), the background is asymmetric. The low sideband region around $E_{K^0_S}/E_{\rm beam} = 0.96$ is contaminated from known hadronic sources such as $K^{*0}(892)\bar{K}^0$+c.c. (both the $\psi(2S)$ [12] and the continuum below the resonance can produce this final state), and the $K^0_S K^0_S$ 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.

In the $\pi^+\pi^-$ and K^+K^- modes the signal yield, N_S, is obtained by subtracting from the observed yield, $S_{\psi(2S)}$, the QED (scaled sideband) contribution, $N_{\rm QED}$, and the scaled contribution, $f_s \cdot N_{\rm cont}$, from the observed yield in the continuum (minus the QED contribution in it), $N_{\rm cont}$. A possible contamination from the $\psi(2S)$ tail in the continuum yield is found to be negligibly small in all the modes. In other words, $N_S = S_{\psi(2S)} - N_{\rm QED} - f_s \cdot N_{\rm cont}$. In the $K^0_S K^0_L$ mode, as stated earlier, there is no QED background. However, one count was observed in the continuum data, leading to $f_s \cdot N_{\rm cont} = 0.3$. In Table I the observed yields and the subtractions are listed, as are the efficiencies calculated using the luminosity weighted average from the simulation studies for the CLEO III and CLEO-c detectors. The branching fractions are obtained as $N_S/[N(\psi(2S)) \cdot \epsilon]$, with $N(\psi(2S)) = 3.08\times10^6$. For $\pi^+\pi^-$ both the measured value and the corresponding 90% confidence upper limit are listed. For $K^0_S K^0_L$ the listed value is obtained using $\mathcal{B}(K^0_S \to \pi^+\pi^-) = (68.95\pm0.14)\%$ [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 in our sample; 1.0% (2.0%) uncertainty in the simulation of our hardware trigger; 1.0% (1.4%) uncertainty in the reconstruction of each charged track in the event; 1.0% and 2.7% (0.6%) uncertainties for kaon and pion identification. Uncertainties in the $\pi^+\pi^-$, K^+K^-, and $K^0_S K^0_L$ modes arising due to background subtraction procedures are 0.2%, 1.4%, and 3.8%; and those due to simulation statistics are 1.3%, 1.6%, and 0.4% respectively. Additional uncertainties in the $\pi^+\pi^-$mode from the $E_{\rm vis}/\sqrt{s}$, $|\Sigma\vec{\mathbf{p}}|/E_{\rm beam}$, and $E_{\rm CC}$ criteria are determined to be 1.4%, 24.3%, and 12.1%, respectively. In the $K^0_S K^0_L$ mode, additional uncertainties arise due to K^0_L selection (3.7%), K^0_S finding (3.0%), and the $\mathcal{B}(K^0_S \to \pi^+\pi^-)$ [13] (0.1%). After combining all contributions in quadrature, the total systematic uncertainties for the $\pi^+\pi^-$, K^+K^-, and $K^0_S K^0_L$ final states are 28.0%, 4.7% and 7.3%, respectively.

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	$S_{\psi(2S)}$	$N_{\rm QED}$	$f_S \cdot N_{\rm cont}$	N_S	$\epsilon(\%)$	$\mathcal{B}(10^{-5})$	$Q(\%)$
$\pi^+\pi^-$	11	<0.1	6.8	4.2	16.7	$0.8\pm0.8\pm0.2$	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	$6.3\pm0.6\pm0.3$	26.6 ± 4.5
$K^0_S K^0_L$	53	-	0.3	52.7	42.8	$5.8\pm0.8\pm0.4$	32.2 ± 5.2

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 $\mathcal{B}_{K^0_S K^0_L}$ 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.

TABLE II: Branching fractions used for determination of strong/EM interference parameters. The statistical and systematic errors have been combined in quadrature. The branching fractions are at the 10^{-5} level.

	DASP [15]	BES [6, 16]	CLEO	World Avg.
$\mathcal{B}_{\pi^+\pi^-}$	8±5	0.84±0.65	0.8±0.8	0.9±0.5
$\mathcal{B}_{K^+K^-}$	10±7	6.1±2.1	6.3±0.7	6.3±0.7
$\mathcal{B}_{K^0_sK^0_L}$	—	5.24±0.67	5.8±0.9	5.4±0.6
$R(\psi(2S))$	—	2.6±1.0	2.8±1.4	2.6±0.7
$\Delta(\psi(2S))$	—	(89±35)°	(93±20)°	(89±14)°

It was noted by both Suzuki [1] and Rosner [2] that the available data for J/ψ did not have enough precision to take account of the small amplitude for the SU(3) breaking strong decay. Neither was it possible to take account of the resonance interference with the continuum. For $\psi(2S)$ 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:

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

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

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]

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

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

As a by-product of this work, from the one count for $K^0_SK^0_L$ observed in the continuum data, we obtain the 90% C.L. of $\sigma_0(K^0_SK^0_L) < 0.74$ pb at $\sqrt{s} = 3.671$ GeV including radiative corrections from the K^+K^- analysis in Ref. [17]. Using the relation [19]

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

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 $|F_{K^0}(s = 13.48\ \mathrm{GeV}^2)| < 0.023$ 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 $s < 4.5\ \mathrm{GeV}^2$ [20].

In conclusion, we have analyzed CLEO III and CLEO-c $\psi(2S)$ data corresponding to 3.08×10^6 $\psi(2S)$ decays, 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°, in contrast to some earlier theoretical speculations [3, 4].

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