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Observation of New Hadronic $\psi(2S)$ Decays at CLEO

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Using 5.46 pb^{-1} of e^+e^- annihilation data collected at the $\psi(2S)$ with the CLEO detector we have observed a variety of new hadronic decay modes of the $\psi(2S)$. A comprehensive set of branching ratios and upper limits is presented.

Keywords: $\psi(2S)$; hadronic decay; 12% rule.

1. Introduction

In perturbative QCD the states J/ψ and $\psi(2S)$ are non-relativistic bound states of a charm and an anti-charm quark. The decays of these states are expected to be dominated by the annihilation of the constituent $c\bar{c}$ into three gluons. The partial width for the decays into an exclusive hadronic state, h, is expected to be proportional to the square of the $c\bar{c}$ wave function overlap at the origin, which is well determined from the leptonic width [1]. Since the strong coupling constant, α_s, is not very different at the J/ψ and $\psi(2S)$ masses, it is expected that for any state h the J/ψ and $\psi(2S)$ branching ratios are related by

$$Q_h = \frac{\mathcal{B}(\psi(2S) \to h)}{\mathcal{B}(J/\psi \to h)} \approx \frac{\mathcal{B}(\psi(2S) \to \ell^+\ell^-)}{\mathcal{B}(J/\psi \to \ell^+\ell^-)} = (12.7 \pm 0.5)\%, \tag{1}$$

where $\mathcal{B}$ denotes a branching fraction, h is a particular hadronic final state, and the leptonic branching fractions are taken from the PDG [1]. This relation is sometimes called "the 12% rule". Modest deviations from the rule are expected [2]. Although the rule works well for some specific decay modes of the $\psi(2S)$, it fails spectacularly for $\psi(2S)$ decays to final states consisting of one vector and one pseudoscalar meson (VP), such as $\rho\pi$.

Values of Q_h have been measured for a wide variety of final states [1]. A recent review [2] of relevant theory and experiment concludes that current theoretical explanations are unsatisfactory. Clearly more experimental results are desirable. This paper presents measurements of the following new decay modes of the $\psi(2S)$: $\pi^+\pi^-\pi^0$, $\rho\pi$, $\omega\pi$, $\rho\eta$, $K^{*0}(892)\bar{K}^0$, $\eta 3\pi$, $\eta' 3\pi$, $2(K^+K^-)$, $p\bar{p}K^+K^-$, $\Lambda\bar{\Lambda}\pi^+\pi^-$, $\Lambda\bar{p}K^+$, $\Lambda\bar{p}K^+\pi^+\pi^-$, and more precise measurements of these previously measured modes: $\phi\pi$, $\omega\eta$, $\phi\eta$, $K^{*+}(892)K^-$, $b_1(1235)\pi$, $2(\pi^+\pi^-)$, $2(\pi^+\pi^-)\pi^0$, $\omega\pi^+\pi^-$, $K^+K^-\pi^+\pi^-$, $\phi\pi^+\pi^-$, ωK^+K^-, ϕK^+K^-, $p\bar{p}\pi^+\pi^-$, $\omega p\bar{p}$, and $\Lambda\bar{\Lambda}$. We also obtain an improved upper limit for $\phi p\bar{p}$. Where applicable, the inclusion of charge conjugate modes is implied. We select intermediate final states in the following decay modes: $\rho \to \pi\pi$, $\pi^0 \to \gamma\gamma$, $\omega \to \pi^+\pi^-\pi^0$, $\phi \to K^+K^-$, $\eta \to \gamma\gamma$ and $\pi^+\pi^-\pi^0$, $K^{*0} \to K^-\pi^+$, $K^{*+} \to K^0_S\pi^+$ and $K^+\pi^0$, $K^0_S \to \pi^+\pi^-$ and $\Lambda \to p\pi^-$.

2. Analysis and Results

The data sample used in this analysis is obtained at the $\psi(2S)$ and the nearby continuum in e^+e^- collisions produced by the Cornell Electron Storage Ring (CESR) and acquired with the CLEO detector. The datasets consist of $\mathcal{L}$=5.46 pb^{-1} on the peak of the $\psi(2S)$ (2.57 pb^{-1} for CLEO III [3], 2.89 pb^{-1} for CLEO-c [4]) and 20.5 pb^{-1} at $\sqrt{s}$=3.67 GeV (all CLEO-c). The nominal scale factor used to normalize continuum yields to $\psi(2S)$ data is $f_{\rm nom} = 0.2645 \pm 0.004$, and is determined from the integrated luminosities of the data sets corrected for the $1/s$ dependence of the cross section, where the error is from the relative luminosity uncertainty. The actual f used for each mode also corrects for the small differences in efficiency between the $\psi(2S)$ and continuum data samples.

Standard requirements are used to select charged particles reconstructed in the tracking system and photon candidates in the CsI calorimeter. Charged particles are identified using a likelihood function that incorporates dE/dx from the drift chamber and information from the RICH. The invariant mass of the decay products from intermediate resonant states such as π^0, η, ρ, ω, ϕ, K^*, K_S and Λ must lie within limits determined from Monte Carlo (MC) studies.

Energy and momentum conservation requirements are imposed on the reconstructed final state hadrons, which have momentum p_i and combined measured energy $E_{\rm vis}$. We require the measured scaled energy $E_{\rm vis}/E_{\rm cm}$ be consistent with unity within experimental resolution, which varies by final state. We require $|\Sigma\mathbf{p_i}|/E_{\rm cm} < 0.02$. Together these requirements suppress backgrounds with missing energy or incorrect mass assignments. The experimental resolutions are smaller than 1% in scaled energy and 2% in scaled momentum.

For the modes with two or more charged pions, two $\pi^{0\prime}$s or an η, we reject $\psi(2S) \to J/\psi X$ ($X = \pi^+\pi^-$, $\pi^0\pi^0$, or η) events in which the mass of any of the following falls within the range $3.05 < m < 3.15$ GeV: the two highest momentum oppositely charged tracks, the recoil mass against the two lowest momentum oppositely charged tracks, or the mass recoiling against the $2\pi^{0\prime}$s or η.

For every final state, a signal selection range in $E_{\rm vis}/E_{\rm cm}$ is determined by MC simulation, and a sideband selection range is defined to measure background. Final states with intermediate particles must satisfy a scaled energy signal selection range requirement identical to the corresponding mode without the intermediate particle; and the event yield is determined from signal and sideband selection ranges of the intermediate particle mass.

The number of events attributable to each $\psi(2S)$ decay mode is obtained by subtracting the number of events in the sideband region and the scaled continuum production from the number of events in the signal region. Interference between $\psi(2S)$ decay and continuum production of the same final state is neglected. The efficiency for each final state is the average obtained from MC simulations for both detector configurations; the two values are typically within a few percent (relative) to each other. No initial state radiation is included in the MC, but final state radiation is accounted for.

We correct the number of signal for the efficiency and normalize to the number of $\psi(2S) \to \pi^+\pi^- J/\psi$, $J/\psi \to \mu^+\mu^-$ decays in the data, which has been determined previously to be $(6.75 \pm 0.12) \times 10^4$ [5]. The resulting relative branching ratios are obtained and then converted to the absolute branching ratios using $\mathcal{B}(\psi(2S) \to \pi^+\pi^- J/\psi) = 0.323 \pm 0.013$ [1] and $\mathcal{B}(J/\psi \to \mu^+\mu^-) = (5.88 \pm 0.10)\%$ [1]. Q_h values are determined using the absolute $\psi(2S)$ branching ratios determined in this analysis and J/ψ branching ratios from [1].

The branching ratios and Q_h values for 2-body modes are given in Table 1, where BES numbers are from [6]; preliminary results for multi-body modes [7] are listed in Table 2.

Table 1. $\psi(2S)$ branding ratios to two-body final states and a comparison to BES and the PDG.

Mode	CLEO (10^{-5})	PDG/BES(10^{-5})	Q_h (%)
$\pi^+\pi^-\pi^0$	$17.7^{+1.5}_{-1.3} \pm 2.7$	$18.1 \pm 1.8 \pm 1.9$	0.8 ± 0.1
$\rho^0\pi^0$	$0.9^{+0.4}_{-0.4} \pm 0.1$		0.2 ± 0.1
$\rho^+\pi^-$	$1.0^{+0.6}_{-0.5} \pm 0.1$		0.1 ± 0.1
$\rho\pi$	$2.0^{+0.7}_{-0.6} \pm 0.2$	$5.1 \pm 0.7 \pm 0.8$	0.2 ± 0.1
$\omega\pi$	$2.3^{+1.1}_{-0.9} \pm 0.2$	$1.87^{+0.68}_{-0.62} \pm .28$	5.6 ± 2.7
$\phi\pi$	< 0.6	< 0.3	
$\rho\eta$	$2.7^{+0.9}_{-0.8} \pm 0.2$	$1.78^{+0.67}_{-0.62} \pm .17$	13.8 ± 5.0
$\omega\eta$	< 1.0	< 1.1	
$\phi\eta$	$1.8^{+1.5}_{-1.0} \pm 0.4$	$3.5 \pm 1.0 \pm 0.6$	2.8 ± 2.3
$K^{*0}\bar{K}^0$	$8.7^{+2.5}_{-2.1} \pm 0.8$	$15.0 \pm 2.1 \pm 1.9$	2.1 ± 0.6
$K^{*+}K^-$	$1.0^{+0.9}_{-0.6} \pm 0.2$	$2.9 \pm 1.3 \pm 0.4$	0.2 ± 0.2
$b_1^0\pi^0$	$20.5^{+4.4}_{-3.8} \pm 2.9$		8.9 ± 3.0
$b_1^+\pi^-$	$36.8 \pm 4.0 \pm 7.4$	32 ± 8	12.3 ± 2.5
$b_1\pi$	$56.6^{+5.5}_{-5.3} \pm 10.8$		10.7 ± 1.9

3. Summary

We have presented first evidence for $\psi(2S)$ decays to $\pi^+\pi^-\pi^0$, $\rho\pi$, $\omega\pi$, $\rho\eta$, and $K^{*0}\bar{K}^0$. Measurements for several other VP channels are also given. The results suggest that, for VP final states, $\psi(2S)$ decays through three gluons are severely suppressed with respect to the 12% rule and the corresponding electromagnetic processes are not. The decay $\psi(2S) \to \pi^+\pi^-\pi^0$ exhibits a $\rho \to \pi\pi$ signal but has a much larger component at higher $\pi\pi$ mass. We also present preliminary branching fractions for seven new multi-body decay modes of the $\psi(2S)$, namely $\eta 3\pi$, $\eta' 3\pi$,

Table 2. $\psi(2S)$ branding ratios to multi-body final states, h, and the corresponding branching ratios at the J/ψ from PDG, and Q_h from Equation (1).

mode	$\mathcal{B}(\psi(2S) \to h)$ (10^{-4})		$Br(J/\psi)$ (10^{-4})	Q_h (%)
h	this work	PDG	PDG	this work
$2(\pi^+\pi^-)$	2.0 ± 0.3	4.5 ± 1.0	40 ± 10	5.0 ± 1.5
$2(\pi^+\pi^-)\pi^0$	23.7 ± 3.3	30 ± 8	337 ± 26	7.0 ± 1.1
$\omega\pi^+\pi^-$	8.0 ± 1.2	4.8 ± 0.9	72 ± 10	11.1 ± 2.3
$\eta 3\pi$	8.5 ± 1.0	-	-	-
$\eta' 3\pi$	4.3 ± 2.0	-	-	-
$K^+K^-\pi^+\pi^-$	6.5 ± 0.9	16 ± 4	72 ± 23	9.0 ± 3.1
$\phi\pi^+\pi^-$	0.9 ± 0.2	1.50 ± 0.28	8.0 ± 1.2	11.4 ± 3.5
ωK^+K^-	1.9 ± 0.4	1.5 ± 0.4	19 ± 4	9.9 ± 2.9
$2(K^+K^-)$	0.6 ± 0.1	-	-	-
ϕK^+K^-	0.7 ± 0.2	0.60 ± 0.22	15.4 ± 2.1	4.7 ± 1.6
$p\bar{p}\pi^+\pi^-$	5.4 ± 0.7	8.0 ± 2.0	60 ± 5	9.0 ± 1.4
$\omega p\bar{p}$	0.5 ± 0.2	0.80 ± 0.32	13 ± 2.5	3.7 ± 1.9
$p\bar{p}K^+K^-$	0.2 ± 0.1	-	-	-
$\phi p\bar{p}$	< 0.18(90%CL)	< 0.26	0.45 ± 0.15	-
$\Lambda\bar{\Lambda}$	3.0 ± 0.5	1.81 ± 0.34	13 ± 1.2	23.4 ± 4.6
$\Lambda\bar{\Lambda}\pi^+\pi^-$	2.7 ± 0.8	-	-	-
$\Lambda\bar{p}K^+$	0.7 ± 0.2	-	8.9 ± 1.6	7.9 ± 2.8
$\Lambda\bar{p}K^+\pi^+\pi^-$	1.2 ± 0.4	-	-	-

$2(K^+K^-)$, $p\bar{p}K^+K^-$, $\Lambda\bar{\Lambda}\pi^+\pi^-$, $\Lambda\bar{p}K^+$, $\Lambda\bar{p}K^+\pi^+\pi^-$, and more precise measurements of nine previously measured modes, which are $2(\pi^+\pi^-)$, $2(\pi^+\pi^-)\pi^0$, $\omega\pi^+\pi^-$, $K^+K^-\pi^+\pi^-$, $\phi\pi^+\pi^-$, ωK^+K^-, ϕK^+K^-, $p\bar{p}\pi^+\pi^-$, $\omega p\bar{p}$, and $\Lambda\bar{\Lambda}$. We also obtain an improved upper limit for $\phi p\bar{p}$. For multi-body decay modes Q_h values are in general lower than, but, in most cases, consistent with the 12% rule.

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