Charmonium decay physics

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Recent experimental results on the decays of charmonium, together with related physics issues, are reviewed. Some future prospects are described.

1. INTRODUCTION

The dramatic discovery of charmonium, the J/ψ and its radial excitation $\psi(2S)$, launched the modern era of particle physics. After a hiatus of about one decade in the 1980's following a period of several-years of intense experimental activity, charmonium physics has emerged again as one of the most exciting areas of experimental high energy physics. A wealth of new data in the last few years has changed greatly the face of this area.

As the "hydrogen atom of strong interaction physics", charmonium states have been studied in many experiments, which basically use three techniques: formation and subsequent cascade decays from e^+e^- annihilations, two virtual photon interactions from high energy e^+e^- collisions and formation from $\bar{p}p$ collisions. At present the Beijing Spectrometer (BES) is the only experiment at the e^+e^- collider (BEPC) to study charmonium physics around the $c\bar{c}$ threshold in e^+e^- annihilations. The detectors at CESR and LEP, such as CLEO, DELPHI, L3, and OPAL, are performing experiments on two photon physics. The Fermilab experiment E760 and its upgraded experiment E835 are studying the direct formation of $c\bar{c}$ states in $\bar{p}p$ annihilations at the Fermilab Antiproton Accumulator Ring. Precision measurements of the $c\bar{c}$ system (masses, widths, decay rates, etc.) are important inputs to test the limit of PQCD and the order of magnitude of relativistic and radiative corrections.

Recent theoretical developments in effective field theories such as nonrelativistic QCD and heavy quark effective theory, lattice gauge theory, and light front quantization suggest that it should be possible to place the theory of charmonium on a rigorous foundation that is derived directly from QCD.

2. REVIEW OF CHARMONIUM DATA

In this section we will review the experimental data of charmonium states below $D\bar{D}$ threshold. The subjects discussed are the mass, width, and other parameters of 1^3S_1,

2^3S_1, ${}^3P_{0,1,2}$, 1^1S_0, 2^1S_0, and 1^1P_1 resonances. We emphasize on the results obtained since 1990.

2.1. 1^3S_1 : J/ψ

A high precision measurement was performed by BES[1] on leptonic branching fractions from a comparison of the exclusive and inclusive processes: $\psi(2S) \to \pi^+\pi^- J/\psi$, with $J/\psi \to l^+l^-$ and $J/\psi \to anything$, which is luminosity independent and almost free of QED backgrounds. The BES[1] obtained values for $B(J/\psi \to e^+e^-) = 5.90 \pm 0.05 \pm 0.10\%$ and $B(J/\psi \to \mu^+\mu^-) = 5.84 \pm 0.06 \pm 0.10\%$. Including BES data, the new world average will have an error less than 1.5 %, which is about a factor of two improvement over the 1998 PDG value[2].

2.2. 2^3S_1 : $\psi(2S)$

E760 has reported the first direct measurement of the total width of the $\psi(2S)$[3], $\Gamma = 306 \pm 36 \pm 16$ keV. Compared to the value derived from a review of all previous data in 1992[4], $\Gamma = 243 \pm 43$ keV, the central value of E760 is larger. E760 performed new measurements on the branching fractions of $\psi(2S)$ decays to $J/\psi\pi^+\pi^-$, $J/\psi\pi^0\pi^0$, and $J/\psi\eta$ and claimed that they are able to make measurements of $B(J/\psi\pi^+\pi^-)$ and $B(J/\psi\pi^0\pi^0)$ with errors comparable to the world average [5]. However, as has been pointed out by Gu and Li[6], there is logical inconsistency in handling of the computational procedure in Ref. [5]. As also pointed out by Gu and Li[6], the ratio of $B(J/\psi\pi^+\pi^-)/B(\mu^+\mu^-)$ measured by E672/E706[7] as equal to $30.2 \pm 7.1 \pm 6.8$, was mistaken for $B(J/\psi\pi^+\pi^-)/B(J/\psi\mu^+\mu^-)$ in PDG 1998[2]. They thus suggested that we not use the 1998 PDG fit values of branching fractions for the $\psi(2S)$ decays to J/ψ plus anything[6]. PDG will provide new fit values for $B(J/\psi + anything)$, $B(J/\psi + neutrals)$, $B(J/\psi\pi^+\pi^-)$, $B(J/\psi\pi^0\pi^0)$, $B(J/\psi\eta)$, $B(\gamma\chi_{c0})$, $B(\gamma\chi_{c1})$, and $B(\gamma\chi_{c2})$ in the next edition by removing the E760 data and correcting the above mistake [8].

Using the world's largest data sample of $\psi(2S)$, BES has measured $\psi(2S)$ branching fractions for a large number of hadronic final states - many for the first time[9-12]. The results for 2-body (light) meson final states will be discussed in the next section in the context of hadronic decay puzzle.

2.3. ${}^3P_{0,1,2}$: χ_{c0}, χ_{c1}, χ_{c2}

The large sample of $\psi(2S)$ decays at BES permits the study of χ_{cJ} decays with unprecedented precision. Using many decay modes of the χ_{c0}, BES has determined $M(\chi_{c0}) = 3414.1 \pm 0.6 \pm 0.8$ MeV [13]. The precision of this measurement represents a substantial improvement over the existing PDG value of 3417.3 ± 2.8[2]. BES also determined the χ_{c0} total width[14], $\Gamma(\chi_{c0}) = 14.3 \pm 2.0 \pm 3.0$ MeV, by selecting a $\pi^+\pi^-$ event sample, using the precisely measured total width of the χ_{c2}[2] to determine the detector resolution and a MC simulation to determine how the resolution changes from $M(\chi_{c2})$ to $M(\chi_{c0})$. Compared with the only existing result of Crystal Ball[15], $\Gamma(\chi_{c0}) = 13.5 \pm 3.3 \pm 4.2$ MeV, which is actually a combination of two measurements with large errors and of only marginal consistency (within 2.2σ), the uncertainty is now reduced from 40% to 25%.

P-wave charmonium states are directly accessible in $\bar{p}p$ annihilations. Precision measurements of the masses and the total widths of the χ_{c1} and χ_{c2} resonances were performed by E760 using the line shape method a few years ago[16]. The results are given in Table 1.

These new values of the masses agree well with earlier measurements[2]; the errors are reduced by more than a factor of two. The width of the χ_{c1} has been measured for the first time; the uncertainty on the χ_{c2} width has been reduced from about 40% to about 10%.

Table 1
E760 measurements of χ_{c1} and χ_{c2} parameters

^3P_J state	Mass (MeV)	Width (MeV)
χ_{c1}	3510.53±0.04 ± 0.12	0.88±0.11 ± 0.08
χ_{c2}	3556.12±0.07 ± 0.12	1.98±0.17 ± 0.07

While there are only upper limits on $\gamma\gamma$ partial width for the χ_{c0} resonance exist so far[14,15], there are a number of measurements for the χ_{c2} made by L3[18,19], E835[20], OPAL[21], CLEO[2,22], E760[2], and TPC[2] since 1990. For χ_{c0}, the limits are $\Gamma_{\gamma\gamma} <$ 6.2 keV reported by CLEO and $<$ 5.5 keV recently by L3 (both 95% C.L.); the only branching fraction measured by Crystal Ball was never actually published[23]. The results for χ_{c2} are summarized in Table 2. Among these data, the central value of $\Gamma_{\gamma\gamma}$ for χ_{c2} differs significantly, and measurements at the e^+e^- colliders (LEP,CESR,PEP) seem all larger than the E760/E835 results obtained in $\bar{p}p$ annihilations. New measurements are still required. A reduction in the discrepancy found between the χ_{c2} data will be of fundamental importance to guide the extraction of theoretical parameters from the data.

Table 2
$\gamma\gamma$ partial width for χ_{c2}

Experiment	$\Gamma_{\gamma\gamma}(\chi_{c2})$ (keV)
L3[18]	$<$ 1.4 (95% C.L)
E835 [20]	0.311± 0.041±0.031 (prelim)
L3[19]	1.02 ±0.40±0.15 ±0.09
OPAL[21]	1.76 ±0.47±0.37±0.15
CLEO[22]	0.7 ±0.2±0.1±0.2
CLEO[2]	1.08 ±0.30±0.26
E760[2]	0.321 ±0.078±0.054
TPC[2]	3.4 ±1.7±0.9

BES performed the first measurement of the branching fraction and the partial width for $\chi_{c0} \to \bar{p}p$[14]. After publication of the BES results for all $\chi_{cJ} \to \bar{p}p$ branching fractions, E835 also reported its first measurements on χ_{c0} and new results on χ_{c1} and χ_{c2}[20]. The results are compared in Table 3 with BES measurements. One notes that E760/E835 results for all $B(\chi_{cJ} \to \bar{p}p)$ are systematically higher (tantalizingly large! - C. Quigg[24]) with respect to BES results, though both have large errors. It has been pointed out[24] that in both experiments the $B_{\bar{p}p}$ and $\Gamma_{\bar{p}p}$ are derived from the product of branching fractions $B_{in} \times B_{out}$ and from $B(\psi(2S) \to \gamma\chi_{cJ})$ and $B(\chi_{cJ} \to \gamma J/\psi)$ respectively. New measurements of these two branching fractions would be desirable to exclude one possible origin of such inconsistency.

Table 3
Comparison of BES and E760/E835 results for χ_{cJ} decays B($\bar{p}p$) $\times 10^4$ (left) and $\Gamma(\bar{p}p)$ in keV (right).

^3P_J	BES	E760/E835	BES	E760/E835
χ_{c0}	1.59 $\pm$0.43$\pm$ 0.53	$4.82^{+0.97+2.08}_{-0.81-1.12}$	2.3$\pm$1.1	$8.0^{+1.9+3.5}_{-1.6-1.9}$
χ_{c1}	0.42$\pm$0.22$\pm$0.28	0.78$\pm$0.10$\pm$0.11 (E835) 0.86 $\pm$ 0.12 (E760)	0.037 $\pm$ 0.032	0.069 $\pm$ 0.009 $\pm$0.010 (E835) 0.076 $\pm$ 0.010 $\pm$0.005 (E760)
χ_{c2}	0.58$\pm$0.31$\pm$0.32	0.91$\pm$0.08$\pm$0.14 (E835) 1.00 $\pm$ 0.11 (E760)	0.116 $\pm$0.090	0.180 $\pm$ 0.016 $\pm$0.026 (E835) 0.197 $\pm$ 0.018 $\pm0.016(E760)$

BES studied many other hadronic decays of P-wave charmonium states, and determined altogether more than 30 branching fractions for χ_{c0}, χ_{c1} and χ_{c2}[12,13] using the PDG values for $B(\psi(2S) \to \gamma\chi_{cJ})$[2]. Among them 15 were measured for the first time.

2.4. 1^1S_0: η_c

In spite of a number of measurements on the mass of η_c, the value remains ambiguous in PDG 1998 edition[2]. The PDG average there is based on a fit to 7 measurements with poor internal consistency and the confidence level is only 0.001. The measurement of E760[25] disagrees with the value of DM2[26] by almost 4σ and is almost 10 MeV different from 1994 PDG average. The change will cause a shift in the value of the hyperfine splitting for the S-wave charmonium states which, in turn, are important in understanding the spin-spin forces.

The value of $M(\eta_c)$ determined recently by BES using several decay modes of the η_c[13] is in excellent agreement with DM2 data and is 2.4σ below the E760 result. More recently, L3 has also reported their measurement on the η_c mass[18], which agrees well both with BES and DM2. A comparison of recent results is shown in Table 4.

New measurements on η_c width was made by E760[25], $\Gamma = 23.9^{+12.6}_{-7.1}$ MeV, and improved by E835 afterwards[20] with $\Gamma = 17.8^{+7.2}_{-6.9}$ MeV (preliminary). The results are still larger than previous measurements[2] where for instance the Crystal Ball value in 1986 is listed as 11.5 ± 4.5 MeV, and the errors remain large. The $\gamma\gamma$ partial width of η_c was measured by a number of experiments, including L3[18], E760/E835[2,20], ARGUS[2] and CLEO[2,22]. Unfortunately, the data are not of sufficient precision to differentiate between theories.

Table 4
Recent data on η_c mass

Experiment	Mass of η_c (MeV)
L3[18]	2974 $\pm$ 18
BES[13]	2975.8 $\pm$ 3.9 $\pm$ 1.2
E760[25]	$2988.3^{+3.3}_{-3.1}$
DM2[26]	2974.4$\pm$1.9
MARK3 [27]	2969 $\pm$4 $\pm$ 4

2.5. 2^1S_0**:** $\eta_c(2S)$

After observation of a candidate of this state by Crystal Ball experiment at 3594 MeV[28], it has been searched for in E835[20], BES[13], DELPHI[29], and L3[18] recently. No evidence is found in the mass region around 3594 MeV by any of the subsequent experiments. This appears to challenge the theoretical analysis of Barnes, Browder, and Tuan [30] based on the relationship that hadronic branching fractions of η_c and $\eta_c(2S)$ to the same exclusive final state channel could be equal[31] and a nonrelativistic quark potential model calculation[32] that $\Gamma(\eta_c(2S) \to \gamma\gamma) = 3.7$ keV. The L3[18] upper limit on $\Gamma_{\gamma\gamma}(\eta_c(2S)) < 2.0$ keV (95% C.L.) is not yet a severe constraint since the model calculation of this partial width might only be good to a factor of 2 to 3[32]. Search for $\eta_c(2S)$ in the two photon process at CESR, which has already delivered more than $11 fb^{-1}$ of integrated luminosity to CLEO, remains a valuable goal. We must caution however that though the important observation that $\gamma\gamma$ widths are not strongly suppressed with radial excitation in any of the $q\bar{q}$ systems considered[30], to date no radial excitations have been identified in $\gamma\gamma$ collisions, so for the present this width calculation should be taken as a theoretical estimate in a regime in which theory has not been tested.

2.6. $^1P_1$**:** $h_c(1P)$

E760 announced the discovery of this state at 3526.14 MeV[33]. In a subsequent search for hidden charm states in π^-− and $p - Li$ interactions, E705 reported the observation of a $J/\psi\pi^+\pi^-$ signal at 3.836 GeV (possible $^3D_2$ state) and a $J/\psi\pi^0$ enhancement at 3.527 GeV (possibly the $^1P_1$ state)[34]. However, E672/E706 has questioned the strong structure at 3.836 GeV[7]. It was also questioned by Barnes, Browder, and Tuan[35] whether E705 could have 'confirmed' E760's discovery of $^1P_1$ state. E835 will continue this work and look further with more data in the near future.

3. CHARMONIUM HADRONIC DECAY PUZZLE

This celebrated "$\rho - \pi$" puzzle with dramatic suppression of $\psi(2S) \to VP$[36,37] and VT[9], but apparent non suppression of $\psi(2S) \to AP, VS$ as well as isospin violating modes $\omega\pi^0$, $\rho\eta^0$ (with branching ratios in accord with PQCD "14%" rule), has been mostly summarized in [38]. We note in particular that BES has concluded that $\psi(2S) \to \omega\pi^0$ is **larger** than (strong) isospin conserving, SU(3)-allowed, $\psi(2S) \to \rho\pi$ decay while large isospin violations are seen between branching fractions for charged and neutral $\psi(2S) \to K^*\bar{K}$ decays.

The failure of most theoretical models up to 1990 have been summarized in Table 5, while those proposed in recent years have been summarized in [39]. Actually the model of Li-Bugg-Zou (LBZ for short) [40], though fortuitous[39], cannot be ruled out. However, based on the final state interaction(FSI), their numerical computation picks only two specific intermediate states in estimating the FSI. As Suzuki[41] pointed out, one can in fact get almost any number by selecting intermediate states of one's choice. Unfortunately the intermediate states picked by LBZ may be heavily dominated by other intermediate states. Hence LBZ model does not answer the question of which specific FSI is responsible for the puzzle.

Table 5
Theoretical models up to 1990 and related experimental results.

Model	Predictions	Experimental results
Brodsky-Lepage-Tuan (1987); Hou-Soni (1983)	Hadron helicity conserved: -$\psi(2S) \to$ VP modes suppressed; -$\psi(2S) \to$ VT modes not suppressed. J/ψ-glueball mixing: -J/ψ shape distorted; -Search in $\psi(2S) \to \pi^+\pi^- O$ -$J/\psi \to \phi f_0$ enhanced.	 -$\psi(2S) \to \omega\pi^0$ not suppressed; -$\psi(2S) \to$ VT suppressed. -Not seen; limits set; -Not seen; limits set. -$\psi(2S) \to \phi f_0$ not suppressed.
Chaichian-Tornqvist (1989)	Energy dependent exponetial form factor: -$\psi(2S)$ 2-body meson modes suppressed; -B($\psi(2S) \to \rho\pi$) $= 7 \times 10^{-5}$	 -$b_1\pi$ and ϕf_0 not suppressed; -B($\psi(2S) \to \rho\pi$) $< 2.8 \times 10^{-5}$.
Pinsky (1990)	$\psi(2S) \to$ VP are hindered M1 transitions: -B($\psi(2S) \to \gamma\eta'$) $= 9 \times 10^{-6}$; -B($\psi(2S) \to \rho\pi$) $= 4 \times 10^{-5}$; -$\psi(2S) \to \omega f_2$ not suppressed.	 -B($\psi(2S) \to \gamma\eta'$) $= 150 \times 10^{-6}$; -B($\psi(2S) \to \rho\pi$) $< 2.8 \times 10^{-5}$; -$\psi(2S) \to \omega f_2$ suppressed.

The most recent model of Gérard and Weyers[42] has the following problems. (a) The BES data[11] that for $\psi(2S) \to AP$ with $K_1(1270)\bar{K}$ (large) and $K_1(1400)\bar{K}$ (small), cannot be clearly understood in the model. (b) The universality assumption for three-gluon hadronization of $\psi(1S)$ remains doubtful[43]. For instance the three gluons from $\psi(1S)$ must certainly hadronizes to say VP and VT final states in different ways. Can the phase really be the same? (c) The model emphasizes on $\psi(2S) \to AP, AS$ final states to leading order. Hence **unsuppressed** $\psi(2S) \to \phi f_0(980)$ [44,12] a VS mode, and $\psi(2S) \to K^{*0}\bar{K}^{*0}$ a VV mode[12] would appear to be at variance with the model. There is a need for further concerted effort on both theoretical and experimental side to provide a **solution** to the $J/\psi/\psi(2S) \to \rho\pi$ puzzle.

The $\rho - \pi$ puzzle motivated the important discovery of long-distance (large phase) FSI physics[45–47] from $J/\psi \to VP, PP, B\bar{B}$ data. **Its resolution remains very important**. For instance Suzuki noted[45] that in B-meson decays knowledge of much higher precision will be needed for FSI phases above the inelastic thresholds, a nearly impossible task for theoretical computation/extraction from scattering data. **Parameters of fundamental interactions** can then only be extracted from data free from FSI (a severe limitation?). Also [47] stressed that FSI in nonleptonic B-decay has been an important unsolved issue in direct search for CP violations.

Rosner did **significant** damage control[48,49] for the future of B-Factory physics. He introduced (i) **universal** FSI as consequence that γ and 3g amplitudes for J/ψ are out of phase ($\simeq \pi/2$) with each other. (ii) Connection is made with charmonium where strong phase shifts in $B \to PP$ arise as result of strong absorptive effects in rescattering of $c\bar{c} \to$ light quarks[48]. (iii) Predicts (c.f. Table VI of [48]) direct CP asymmetries in $B^0(\bar{B}^0) \to K^+\pi^-(K^-\pi^+)$, $B^\pm \to K^\pm\pi^0$ maximally ~ 0.34. (iv) Emphasized decays of neutral B mesons to CP eigenstates such as $J/\psi K^0_S$ and $\pi\pi$ can directly probe CKM phases, since their interpretation is **immune from strong FSI**. Hence recent measurement of $sin2\beta$ [50], a CP violating parameter, remains valid. (v) Suzuki [51] has continued this favorable ambiance with a very recent paper on testing direct CP violation of standard model **without knowing strong phases**.

Since **large CP asymmetry would require large FSI**[43], CLEO III with a single ring and a well tried detector (suitably upgraded) could be decisive in the study of CP asymmetries for $B^0(\bar{B}^0) \to K^+\pi^-(K^-\pi^+)$, $B^\pm \to K^\pm\pi^0$ before year end.

Emphasis on $J/\psi/\psi(2S)$ physics should not detract us from the significant physics to be done in the open charm domain. For instance, the D can be fully reconstructed in $\psi''(3.772) \to D\bar{D}$, while $\bar{D} \to \mu + \nu$ can be deployed to measure f_D. Currently $f_D < 290$ MeV and $f_{D_s} = 250$MeV, while $SU(3)$ breaking suggests $f_{D_s}/f_D = 1.1 - 1.25$, so $f_D \sim 200 - 220$ MeV (an attainable experimental goal). Grinstein[52] says that up to 5%, we have

$$f_{B_s}/f_B \simeq f_{D_s}/f_D, \text{ and } [\Delta M_s/\Delta M_d]^{1/2} \simeq \frac{|V_{ts}|}{|V_{td}|}(f_{B_s}/f_B) \tag{1}$$

where ΔM_s and ΔM_d are $B\bar{B}$ splittings in strange/non strange B respectively. So we are again back to **fundamentals** of measuring CKM matrix elements! Finally with the advent of a Tau-Charm Factory, we must not forget about exploration of molecular charmonium states as discussed recently[53].

4. FUTURE PROSPECTS

E835 experiment will continue to take data during 1999-2000 period, with $20pb^{-1}$ accumulation of χ_{c0}, $100pb^{-1}$ of $\eta_c(2S)$, and $200pb^{-1}$ of $\psi(^1P_1)$ anticipated respectively. At the forthcoming run at BES, accumulation of $5 \times 10^7 J/\psi$ are expected, while there is a proposal for $2 \times 10^7 \psi(2S)$ run. It is to be hoped that there will also be a run at $\psi''(3.772)$ for open charm study. Then there are the B-Factories Babar/PEP II, Belle/KEK-B **and CLEO III**. Many in the high energy physics community feel that charm spectroscopy both below and above $D\bar{D}$ threshold is fascinating and badly needs a new high statistics facility. A Tau-Charm Factory with luminosity about two orders of magnitude higher than the BEPC would fill this need.

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