Charmonium Physics in a Tau Charm Factory

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Abstract

The present status of the charmonium system is reviewed. Emphasis is placed on the following issues: the hadronic decay puzzle; search for the vector glueball; confirmation of the $\eta_c(2S)$ and $hc1$ states; the χ_c physics. The possibilities at a future Tau Charm Factory are discussed.

Charmonium Physics in a τCF

1. **Introduction**
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3. **Vector Glueball**
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1 Introduction

A wealth of information has been obtained through intense studies of the charmonium system (mostly J/ψ physics) for two decades after the "November Revolution". However, the present precision in heavy-flavor experiments is only good enough to study the gross properties of the c and b quarks. The purpose of the proposed Tau Charm Factory is to measure the properties of the τ lepton and the c quark with precisions comparable to the ones attained for the light fermions. The Tau Charm Factory would cover a broad physics program with the ultimate aim to answer the many unanswered questions lefted by the Standard Model, in spite of its enormous phenomenological success. This program contains three main elements: (1) Precision test of the electrowak parameters; (2) Precision test of QCD at the interface of perturbative and non-perturbative dynamics; and (3) Search for new physics.

The charmonium system is a superb QCD laboratory. The τ and D systems provide several interesting topics in QCD; nevertheless, the richest system for QCD studies comes from the J/ψ , $\psi(2S)$, η_c, and, possibly, other charmonium states. Also, there will be interesting possibilities for the charmonium to reveal the clues to the physics beyond the Standard Model.

The spectrum of the charmonium states in shown in Fig. 1. The special running energies at an e^+e^- collider for charmonium studies are the J/ψ and $\psi(2S)$ resonances. Since other states with quantum numbers other than 1^{--} can be produced only from the cascade decays of the $\psi(2S)$, the $\psi(2S)$ becomes a unique source of all charmonium states below the open charm threshold. Therefore, the physics at the $\psi(2S)$ is in fact the whole charmonium physics below the open charm threshold.

In a Tau Charm Factory, with a design luminosity of $10^{33} cm^{-2} s^{-1}$, running at 3.686 GeV, 4×10^9 $\psi(2S)$'s would be produced in one year, giving rise to the secondary production of 10^9 tagged J/ψ's (through $\psi(2S) \to J/\psi\pi^+\pi^-$), 3×10^8 events of each type of $\chi_{c1,2,3}$'s (via $\psi(2S) \to \gamma\chi_{cJ}$), and 10^7 $\eta_c(1S)$'s and $\eta_c(2S)$'s (through the radiative decays $\psi(2S) \to \eta_c\gamma$).

Table 1 presents a comparison of the Tau Charm Factory with previous e^+e^- colliders, SPEAR and BEPC, working at similar energy region. Table 2 shows the performance of the detector used for the Tau Charm Factory, in comparison with detectors previously used for the SPEAR and the BEPC. The charmonium physics in a Tau Charm Factory will benefit enormously from the ultra-high statistics and improvements from better detector capabilities including: high resolution and efficient electromagnetic calorimetry; uniform charged and neutral track acceptance; and very large solid angle and very forward angle acceptance.

At present and in the next few years, the BEPC is the only e^+e^- machine capable of

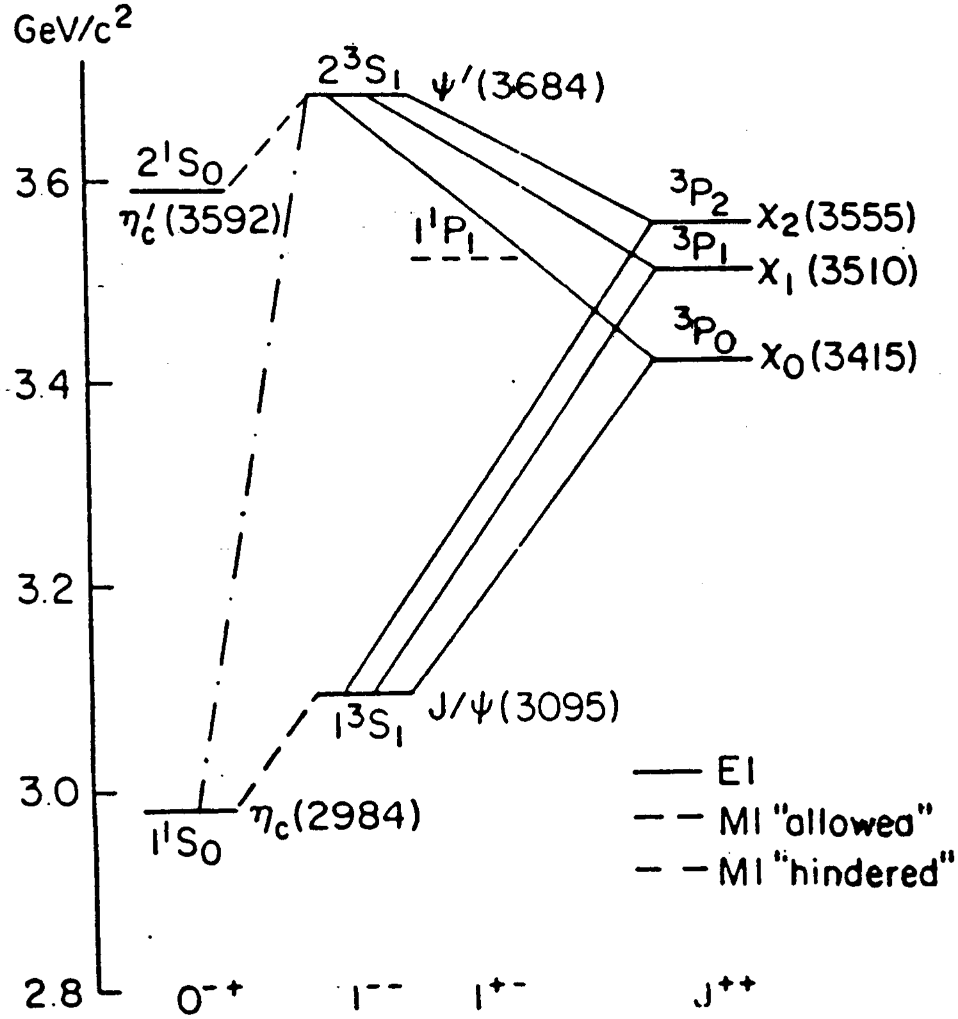
GeV/c²
3.6
3.4
3.2
3.0
2.8
2¹S₀
η'c (3592)
2³S₁
ψ'(3684)
1¹P₁
³P₂
χ₂(3555)
³P₁
χ₁ (3510)
³P₀
χ₀(3415)
1³S₁
J/ψ(3095)
1¹S₀
ηc(2984)
E1
M1 "allowed"
M1 "hindered"
0⁻⁺
1⁻⁻
1⁺⁻
J⁺⁺

Table 1. Comparison of e^-e^+ colliders with beam energy close to 2 GeV.

		SPEAR	BEPC	TCF
Number of bunches	k_b	1	1	30
Bunch Spacing	S_b [m]	234	240	12
Total Beam Current	I [mA]	10	50	570
Vertical β-fn. at IP	β_y^*[m]	0.08	0.10	0.01
Beam-Beam tune shift	ξ_y	0.025	0.04	0.04
Luminosity	$L[cm^{-2}s^{-1}]$	10^{30}	10^{31}	10^{33}

Table 2. Detector performance comparison.

	Mark III/ BES	TCF
Charged Particles:		
Momentum resol: σ_p/p (GeV/c)	$1.5\% p \oplus 1.5\%/\beta$ [MkIII] $0.7\%p \oplus 1.3\%/\beta$ [BES]	$0.3\%p \oplus 0.3\%/\beta$
Ω (barrel) (x 4π str.),	70%	90%
Photons:		
Energy resolution : σ_E/E (GeV)	$17\% / \sqrt{E}$	$1\%/E^{1/4} \oplus 1\%$
Angular resolution : $\sigma_{\theta,\ \phi}$(mr)	10 [MkIII] , 5[BES]	$5/\sqrt{E}$
2γ angular separation : $\Delta\theta_{2\gamma}$ (mr)	20	50
E^{γ}_{min} (MeV)	100	10
Particle identification:		
$h \rightarrow e$ rejection	4% at 0.5 GeV/c	0.1%
$h \rightarrow \mu$ rejection	5% at 1.0 GeV/c	0.1%/p + 1%
$\pi \rightarrow K$ rejection	3σ at 0.7 GeV/c	3σ at 1.0 GeV/c
K^0_L/n detection efficiency	62%	95%
ν tagging	– – ––	from 100 MeV

running at the J/ψ and $\psi(2S)$. In the late 1980s, there was yet an experiment on the study of charmonium spectroscopy in $p\bar{p}$ annihilations at the Fermilab Antiproton Accumulator Ring, the experiment E760. A next generation of this experiment, E835, to continue the study of charmonium, will start its data-taking in the middle of 1995. In restudy the physics potential of the Tau Charm Factory in the era of B-Factory and CESR, it seems also need to consider the possible contributions of these facilities as well as the precisions they can reach in the study of charmonium physics.

In this paper, we focus the main discussion on the following physics topics: the hadronic decay puzzle; search for the vector glueball; confirmation of the $\eta_c(2S)$ and h_{c1} states; and the physics at the χ_c.

2 Hadronic Decay Puzzle

Hadronic decays of the J/ψ and $\psi(2S)$ were very puzzling, and are even puzzling now.

According to the PQCD, the hadronic decay rate of the $\psi(2S)$ relative to the J/ψ should scale as the ratio of the three gluon widths which are proportional to the leptonic widthe divided by the full widths

$$\frac{B(\psi(2S)\to hadrons)}{B(J/\psi\to hadrons)}=\frac{B(\psi(2S)\to ggg)}{B(J/\psi\to ggg)}\cong\frac{B(\psi(2S)\to e^+e^-)}{B(J/\psi\to e^+e^-)}=(14\pm 2)\%$$

"14% *rule*"

Experimentally, the MARKII group measured several decays in 1982 and first found this rule is observed for most of the hadronic modes except the vector-pseudoscalar decays $\rho\pi$ and $K^*\bar{K}$.

In 1985, a Ph.D thesis completed in the Crystal Ball group (unpublished) reported the observation of the radiative decay to the tensor $f(1270)$, but neither to the η nor to the η'.

More recently, the MARKIII group remeasured the $\rho\pi$ decay in a new sample of $\psi(2S)$ and set a preliminary upper limit slightly below the MARKII one.

Table 3 shows the hadronic decays that have been measured.

Table 3. Experimental $\psi(2S)/J/\psi$ Ratios (RPP)

mode	$B(\psi(2S))$	$B(\psi(2S))/B(J/\psi)$
"$ggg+\gamma gg$"	0.15 ± 0.04	0.21 ± 0.06
$3(\pi^+\pi^-)\pi^0$	$(3.5\pm1.6)\times10^{-3}$	0.12 ± 0.06
$2(\pi^+\pi^-)\pi^0$	$(3.1\pm0.7)\times10^{-3}$	0.09 ± 0.02
$\pi^+\pi^-\pi^0$	$(8\pm5)\times10^{-5}$	0.005 ± 0.003
$2(\pi^+\pi^-)$	$(4.5\pm1.0)\times10^{-4}$	0.11 ± 0.04
$\pi^+\pi^-$	$(8\pm5)\times10^{-5}$	0.5 ± 0.4
$\rho\pi$	$<8.3\times10^{-5}$	<0.0065
$\pi^+\pi^-K^+K^-$	$(1.6\pm0.4)\times10^{-3}$	0.22 ± 0.09
K^+K^-	$(1.0\pm0.7)\times10^{-4}$	0.42 ± 0.30
$K^+\bar{K}^{*-}+c.c.$	1.8×10^{-5}	<0.004
$\pi^+\pi^-p\bar{p}$	$(8.0\pm2.0)\times10^{-4}$	0.13 ± 0.04
$p\bar{p}$	$(1.9\pm0.5)\times10^{-4}$	0.09 ± 0.02
$p\bar{p}\pi^0$	$(1.4\pm0.5)\times10^{-4}$	0.13 ± 0.05
$\Lambda\bar{\Lambda}$	$<4\times10^{-4}$	<0.3
$\Xi^-\Xi^+$	$<2\times10^{-4}$	<0.14
$\gamma\pi^0$	$<5.4\times10^{-3}$	<140
$\gamma\eta'$	$<1.1\times10^{-3}$	<0.25
$\gamma\eta$	$<2\times10^{-4}$	<0.23
$\gamma\eta(1420)\to\gamma K\bar{K}\pi$	$<1.2\times10^{-4}$	<0.16

From these results people afirm that the puzzle is associated only with the vector–pseudoscalar final states.

Very recently, the BES collaboration has produced some new and exciting measurements of the $\psi(2S)$ hadronic decays from 1.27×10^6 $\psi(2S)$ decays.

1) Confirm the previously observed anomaly of $\psi(2S)\to\rho\pi$ suppression, and set a new upper limit of

$$B(\psi(2S)\to\rho\pi)<5.1\times10^{-5}\ \ (90\%\ C.L.),$$

compared to

$$MKII \qquad <8.3\times10^{-5}\ \ (90\%\ C.L.)\ \&$$

$$MKIII \qquad <7.0\times10^{-5}\ \ (90\%\ C.L.).$$

2) Discover a new suppression mode in $\psi(2S)$ hadronic decays, which is not a vector–pseudoscalar.

Table 4 shows the results obtained from the analysis of $\psi(2S)\to2(\pi^+\pi^-)\pi^0$ decays (together with the PDG data of J/ψ).

Table 4. BES results from analysis of $\psi(2S)\to2(\pi^+\pi^-)\pi^0$

mode	$B(\psi(2S)), 10^{-4}$		$B(J/\psi), 10^{-3}$	$B(\psi(2S))/B(J/\psi)$
	BES	PDG	PDG	
$2(\pi^+\pi^-)\pi^0$	$29 \pm 2 \pm 6$	31 ± 7	33.7 ± 2.6	9
$\omega\pi^+\pi^-$	$3.6 \pm 1.1 \pm 0.8$	—	7.2 ± 1.0	5
$b_1^\pm\pi^\mp$	$3.0 \pm 1.0 \pm 0.8$	—	3.0 ± 0.5	10
$\omega f_2(1270)$	< 0.9 (90% $C.L.$)	—	4.3 ± 0.6	< 2

The suppression of the $\omega f_2(1270)$ mode is evident both from the direct measurement of its branching ratio and from the comparison of the branching ratios for $\omega\pi^+\pi^-$ and $b_1^\pm\pi^\mp$ in $\psi(2S)$ and J/ψ decays, noting that $b_1^\pm\pi^\mp$ and $\omega f_2(1270)$ are the two dominant modes that decay into $\omega\pi^+\pi^-$. This discovery is significant because it provides the first example of a new suppression mode, vector–tensor suppression, in $\psi(2S)$ hadronic decays, and changes the long–time adopted picture that the anomaly in charmonium hadronic decays is uniquely seen in the vector–pseudoscalar final states. Now the puzzle extends beyond VP!

The results on the hadronic decays of charmonium are theoretically puzzling and indicate that we really do not understand the detailed process of hadronization when these gluons annihilate into hadrons.

We would summarize the experimental situation with following comments:

1. There are in fact only three missing modes of $\psi(2S)$ decays revealed in experiments, namely $\rho\pi$, $K^*\bar{K}$ and the new finding ωf_2. Convincing evidence for the suppression of the VP final states, where the vector may be a photon, such as $\gamma\eta$, $\gamma\eta'$ and $\gamma\eta(1440)$ modes does not exist so far. As is seen from the table (where 1992 PDG values are used), the measured upper limits of the ratio $B(\psi(2S))/B(J/\psi)$ for $\gamma\pi^0$, $\gamma\eta$, $\gamma\eta'$ and $\gamma\eta(1440)$ are all even higher than 14%. Therefore, we cannot jump at a conclusion that the suppression applies to all (or almost all) VP modes.

2. There is only qualitative test of the PQCD prediction. The agreement of the experimental measurements with the predicted 14% value is at a level of 20 – 80%. For those "missing" modes, no exact size of suppression has been measured. Detailed studies are clearly demanded.

3. It is an experimental fact that most J/ψ decays leading to three (or more) stable or unstable particles proceed doninantly via two–body intermediate states. For example:

$\omega\pi^+\pi^-$	$\pi^+\pi^-\pi^0$	$\phi\pi\pi$
$b_1\pi$	$\rho\pi$	$\phi f_0(975)$
ωf_2		$\phi f_2(1270)$
		$\phi f_0(1300)$
		$\phi f_2(1720)$

Therefore the ratio $B(\psi(2S))/B(J/\psi)$ for these decays into three or more particles usually cannot be used as a straightforward measure for testing the "14% rule". One has to substract individual two–body channels to get the pure non-resonant multi-body decays. Hereafter we will concentrate our analysis mainly on two–body decays.

In next few years, our knowledge on the hadronic decay puzzle is obviously going to be further improved at the BEPC. With 4—5 millions of $\psi(2S)$ data set in 1994/1995, and hopefully (1—2)$\times 10^7$ after upgrade, the BES experiment can finally reach a level roughly corresponding to a branching ratio sensitivity of 10^{-6}. By systematic study of a series of two-body decay modes in VT, VP, and other pair combinations, it would be able to learn with increased precision about the degree of satisfaction of the " 14% rule " for those normal decays, to further test the perturbative QCD theorem, and to measure definite size of suppression for a few missing decays as $\rho\pi$, $K^*\bar{K}$ and $\omega f_2(1270)$.

It is expected that an more accurate and exhaustive study of this puzzle will be completed at the Tau Charm Factory. Assume an initial run that obtains 10^8 produced $\psi(2S)$. This data sample, with 50% reconstruction efficiency, corresponds to a branching fraction sensitivity of 4×10^{-8}. Such a precision is well below any of the theoretical predictions for most of the final states of interest. Analyses with a wealth of high precision data on the $\psi(2S)$ and J/ψ decays would eventually enable to find the clue to the mystery.

It should be pointed out that the detailed comparison of corresponding decays for $\psi(2S)$ and J/ψ is not only the proper approach to solving the above discussed puzzle, but also found useful in clarifying the nature of light hadrons which have been observed in J/ψ decays, either $q\bar{q}$ mesons, glueballs or threshold effects. For example, by using the high statistics at the Tau Charm Factory, one can measure the decays like $\psi(2S) \to \gamma\rho\rho$, $\gamma\omega\omega$, $\gamma K^*\bar{K}^*$, and $\gamma\phi\phi$ for probing the 0^{-+} structures near thresholds in J/ψ radiative decays (so called pseudoscalar puzzle).

3 Vector Glueball

While experiment and theory have largely focused on glueballs composed of two self-interacting gluons, gluonium states consisting of three gluons should also exist.

A trigluonium with $J^{PC} = 1^{--}$, $\mathcal{O}$, was first postulated by Freund and Nambu based on OZI dynamics soon after the discovery of the J/ψ and $\psi(2S)$. Among others, they predicted that the $\mathcal{O}$ would decay copiously into $\rho\pi$, $K^*\bar{K}$, and possibly $\omega\pi\pi$, with severely suppression of decays into other modes like e^+e^- and $\mu^+\mu^-$.

So far the mass of the $\mathcal{O}$ has not been predicted definitely; however, 2—3 GeV region seems reasonable. The search for the $\mathcal{O}$ could be done in three gluon sources such as the two pion decay of the $\psi(2S)$. The reactions $J/\psi(\psi(2S)) \to \pi\pi(or\ \eta,\ \eta')\mathcal{O}$ is proposed as possible factories for producing the $\mathcal{O}$. For $\mathcal{O}$ of mass too close to the J/ψ the phase availability could seriously limit some of these possibilities.

While the vector glueball exists in its own right, attempts also have been made to relate it to the hadronic decay puzzle of charmonium. Hou and Soni first proposed the $\mathcal{O}$ as the particle whose mixing with the J/ψ was responsible for the anomaly. Brodsky, Lepage and Tuan refined this notion with the observation that the vector-pseudoscalar final states are suppressed by the QCD theorem for J/ψ decays, but not for decays of the vector glueball. According to them, the glueball must in fact lie within 80 MeV of the J/ψ.

Recently, G.D. Chao, Y.F. Gu, and S.F. Tuan addressed the problem of trigluonia in charmonium physics (see BIHEP-TH-93-45 / PUTP-93-24). They examined the vector glueball mixing idea and put forward the following arguments:

(1) The $\mathcal{O} - J/\psi$ mixing cannot be very large no matter whether they are nearly degenerate in mass.

(2) The most favorable process $\psi(2S) \to \pi\pi\mathcal{O}$ may have an appreciable branching ratio only if the $\mathcal{O}$ has a decay width to $\rho\pi$ much narrower than normal hadronic width. Assuming $\Gamma(\mathcal{O} \to \rho\pi) = 1 - 10$ MeV, then $B(\psi(2S) \to \pi\pi\mathcal{O}) = O(10^{-3} - 10^{-4})$.

(3) If the $\mathcal{O}$ has a normal hadronic width, $\Gamma(\mathcal{O} \to \rho\pi) \cong 50$ MeV, then $\sin^2\theta = 2 \times 10^{-5}$ and $B(\psi(2S) \to \pi\pi\mathcal{O}) = O(10^{-4} - 10^{-5})$. In this case, it would be more difficult to find the $\mathcal{O}$.

There has never been a serious attempt to search for the vector glueball since its prediction. The major $\psi(2S)$ data sets collected previously were insufficient for such a study.

Recently, the BES started its initial exploration by using 1.27×10^6 $\psi(2S)$ data sample, no signicant structure near the J/ψ can be observed in the invariant mass spectrum of $\rho\pi$ from the $\psi(2S) \to \pi\pi\rho\pi$ decay. However, there is still some hope to observe it with increased statistics at the BEPC provided that the rate of its production in $\psi(2S) \to \pi\pi\mathcal{O}$ is at the level of 10^{-4}.

It has been pointed out that the vector gluonium is considerably clean to find in comparison with gluonia with other quantum numbers (say 0^{-+}, 0^{++} or 2^{++}). However, lacking precise prediction either for mass or width would bring about some difficulty. If nothing is seen from the $\psi(2S)$, one may have to extend the search to higher e^+e^- energies to allow the possibility of more massive resonances.

With its very high statistics and excellent environment, the Tau Charm Factory will certainly be able to perform an exhaustive analysis at a level of 10^{-5} or even less in branching ratio. The unambigious identification of a vector glueball would be a fundamental discovery.

4 $\eta_c(2S)$ and h_{c1} (or $^1P_1$)

The only evidence for the $\eta_c(2S)$ comes from the Crystal Ball experiment at SPEAR which measured a mass difference of ~ 90 MeV between the $\eta_c(2S)$ and $\psi(2S)$. This large difference is hard to reconcile with theoretical predictions unless coupled channel effects are large. It is important to confirm the result of the CB experiment and to measure accurately the mass and the total width of the $\eta_c(2S)$ and its branching ratios to $\gamma\gamma$ and hadronic final states.

E760 started but did not complete a search for the $\eta_c(2S)$. At this time no conclusion can be drawn from their data taken in 1991.

Both E835 and BES have plan to look for the $\eta_c(2S)$ and measure its properties with their new data set scheduled to take in 1994 and 1995, respectively.

The BES collaboration investigated the opportunity of finding $\eta_c(2S)$ at the BEPC, starting from the relation of the hadronic decay rates of the $\eta_c(2S)$ and the $\eta_c(1S)$ deduced by Chao, Gu and Tuan (see BIHEP–TH–93–45 / PUTP–93–24) :

$$B(\eta_c(2S) \rightarrow h) \cong B(\eta_c(1S) \rightarrow h)$$

(In contrast to Anselmino et al., who assume, for any normal light hadronic channel h,

$$\frac{B(\eta_c(2S) \rightarrow h)}{B(\eta_c(1S) \rightarrow h} \cong \frac{B(\psi(2S) \rightarrow h)}{B(J/\psi \rightarrow h)} = 0.14 \text{ .)}$$

It is expected that the best hope is to look for

$$\begin{aligned} \psi(2S) \rightarrow \gamma\eta_c&(2S) \\ &\hookrightarrow uds \text{ hadrons.} \end{aligned}$$

Assuming $B(\psi(2S) \rightarrow \gamma\eta_c(2S)) = 0.4\%$ (0.2—1.3% from Crystal Ball experiment, which is smaller by a factor of ~ 2 than theoretical expectation) , with 5×10^6 $\psi(2S)$ this would correspond to 20k $\eta_c(2S)$ produced. If average efficiency is 5%, it should be possible to detect this state in individual decay modes such as $\pi^+\pi^-K^+K^-$, $K\bar{K}\pi$, $\eta\pi\pi$, $\eta'\pi\pi$ and $\rho\rho$. Since the potentially serious background in this experiment is $\psi(2S) \rightarrow \gamma + \chi_{c2}$, the BES should first measure the χ_c branching ratios, and study the consequences for $\eta_c(2S)$ detection by Monte Carlo simulation.

Whatever the outcomes at the BES or E835, the Tau Charm Factory would of course observe the monochromatic photon signal ininclusive $\psi(2S)$ radiative decays for the $\eta_c(2S)$ very easily. With 10^8 $\psi(2S)$'s this would correspond to 750k produced according to the branching fraction obtained by the Crystal Ball experiment. The Tau Charm Factory would of course confirm it also in specific decay modes and measure its properties including the accurate mass, width, spin-parity and branching ratios. Following the example of J/ψ and $\psi(2S)$, a detailed comparison of the hadronic decays of the $\eta_c(1S)$ and $\eta_c(2S)$ would be an interesting topic in this new area of charmonium physics.

The only experiment which can at present study the $^1P_1$ state is apparently E835 at Fermilab, which is the successor of E760. However, its ability of study will still be limited both by the statistics to be accumulated and by the perfomance of the detector itself.

The BES has planned to initiate its search for $^1P_1$ in $\psi(2S) \to \pi^0 + {}^1p_1, \;\; {}^1p_1 \to \gamma\eta_c$, where η_c decays into various exclusive hadronic decay modes, when a data sample of ~ 5 million $\psi(2S)$'s is collected. Using the limit from the Crystal Ball experiment for the cascade $\psi(2S) \to \pi^0 + {}^1p_1, \;\; {}^1p_1 \to \gamma\eta_c$ which is 0.16%, one expects a maximum of 8000 events for this cascade. If the average efficiency is 5%, this gives signal of several tens at the most from the η_c decays into final states such as $\pi^+\pi^-K^+K^-$, $K\bar{K}\pi$, $\eta\pi\pi$, $\eta'\pi\pi$ and $\rho\rho$. Backgrounds from radiative decay of $\psi(2S)$ into η_c and other sources need careful study for this search.

Since so far exists only a upper limit for the cascade of interest, there is pessimistic view to observe the $^1P_1$ state at the e^+e^- collider. Whatever the consequence at the BES, the Tau Charm Factory will remain the unique facility to perform comprehensive study of the $^1P_1$ issue, which knowledge is useful to solve a number of open questions in heavy quark system.

5 χ_c Physics

Among the charmonium family, though χ_c triplet are the earliest members besides the J/ψ and its radiation excitation, $\psi(2S)$, very little is known about the hadronic decays of these states. Only recently, more discussions on the physics possibilities with the χ_c states appears in the lituature.

At the e^+e^- colliders, there has been basically no new data on the χ_{cJ} states since the Crystal Ball left the SPEAR in 1982. Some new results emerged first from an unfortunately short-lived experiment R104, followed by another experiment of same type E760, on the precision measurements of the mass and width of the χ_{c1} and χ_{c2} states, angular distributions for the process $p\bar{p} \to \chi_{c2} \to J/\psi\gamma \to e^+e^-\gamma$, and decay rate for $\chi_{c2} \to \gamma\gamma$.

The BES experiment is going to resume the study of χ_c at the e^+e^- collider after a decade standstill. By using 1.27 million of $\psi(2S)$'s, clear χ_c states are seen in the $\gamma 4\pi^\pm$ final state. Besides measurement of the branching ratios relevant to the study of the background in a search for the $\eta_c(2S)$, the interesting objective is to observe new decays involving hadronic resonances with increasing statistics. It's evident that the BES will contribute more new results on the χ_c physics in next few years.

At the Tau Charm Factory, it is expected that, in a single month of running at $\psi(2S)$, one may obtain about 4×10^7 χ_c's in $\psi(2S) \to \gamma\chi_c$. This is already a factor of 10^2 more than the present world total. With this statistics the physics output from χ_c decays could exceed that already known from the J/ψ.

1. The huge number of the produced χ_c's can be used to constrain the partial wave analysis of hadronic decays, by fixing the spin J of the initial χ_c. This may make significant inroads into understanding the spectroscopy of light hadrons. For example, $\chi_{c0} \to f_0(975)$ or $a_0(980)+0^{++}$ provides a gateway to 0^{++} hadrons, and $\chi_{c1} \to \pi+1^{-+}$ directly accesses the I=1 exotic partial wave $J^{PC} = 1^{-+}$. Any resonance in this way simply cannot be $q\bar{q}$. $\chi_{c1} \to \pi H$ is sensitive to the light hybrid H, with $J^{PC} = 1^{-+}$ which may occur in the $1.5 \sim 2$ GeV region.

2. Noting that J^{PC} of χ_{c0} is 0^{++}, its decays to glueball pairs might be enriched. It would be interesting to measure $\pi^+\pi^-\eta\eta$, $\pi^+\pi^-\eta\eta'$, $\eta\eta\eta'\eta'$, $K\bar{K}\pi K\bar{K}\pi$ in addition to $2(\pi^+\pi^-)$ and $\pi^+\pi^-K^+K^-$, and look for the 0^{++} and 0^{-+} glueball candidates (0^{++}: $f_0(975)$, $f_0(1400)$, $f_0(1590)$, $f_0(1710)$; 0^{-+}: $\eta(1440)$) in these decays.

3. Possible anomalous magnetic moment of the c quark can be studied by measuring the angular distributions of the E1 transition in the reaction $\chi_{cJ} \to J/\psi\gamma \to e^+e^-\gamma$. The E760 experiment did such a measurement and found a result consistent with zero anomalous moment, but the error are rather large. The measurement of the quadrupole amplitude in the radiative decay a_2 achieved an accuracy of 0.06 for both χ_2 and χ_1. It would be very interesting to reduce the uncertainty at a Tau Charm Factory. The TCF detector, being well suited for such measurements because of its extremely low threshold and excellent hemeticity, can easily reach a factor of 10 higher precision in a single–month's run at 10^{33} luminosity.

6 Summary

1. Charmonium physics remains unique to the Tau Charm Factory.

2. Seeing that the Tau Charm factory is a tool of precision measurement, one of the important issues in charmonium physics program is to perform systematic measurements with high precision, namely the detailed comparison of hadronic (and radiative) decays for $\psi(2S)$ and J/ψ, and for η_c and $\eta_c(2S)$ (when found).

3. Another important issue in charmonium physics program is to study the physics of charmonium states of second ~~generation~~ production in e^+e^-, including χ_c's, η_c's and h_{c1} (if found).

4. Nobody will forget to search for new physics.