Open Topics in Charmonium Physics

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Abstract

The current status of the charmonium system is reviewed. Several interesting issues are discussed: The absolute branching ratio of $\psi \to \gamma\eta_c$ and $\psi' \to \gamma\eta_c'$; the full width and the $\gamma\gamma$ width of the η_c and η_c'; the three photon decay of the ψ; and hadronic decays of the η_c. Predictions for the rates of these processes at a future Tau Charm Factory are presented.

1. Introduction

Fifteen years after its discovery, the charmonium system (Fig. 1) still poses many unanswered experimental and theoretical questions.

Potential and dispersion-relation models predict, in lowest order quantum chromodynamics (QCD), the spectrum of the states, their widths and radiative transition rates. In this picture several topics are in need of a better theoretical and experimental understanding: there is one particle predicted by theory which has not been observed experimentally, the $^1P_1$ state, h_c; the η_c' has only been observed as the recoil mass of a photon coming from ψ' decays, and needs confirmation. The full width of the η_c has a large experimental error, and the width of the η_c' has not been measured. The theoretical predictions and experimental measurements of the two photon width of the η_c have a large uncertainty.

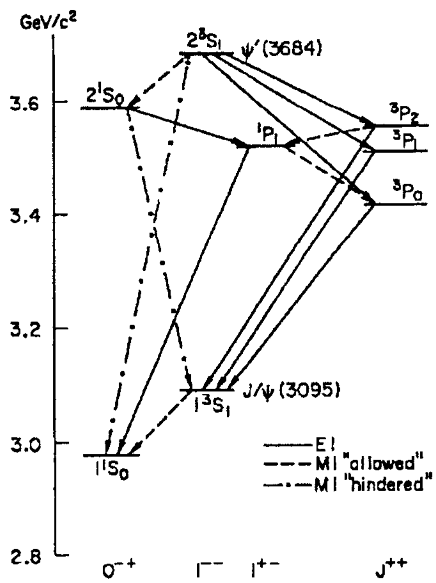

Figure 1: The charmonium system.

In this paper the theoretical and experimental status of these topics are reviewed. Several experiments have studied this region. Most results have come from the Crystal Ball and the Three Marks (Mark I, Mark II, and Mark III) collaborations. Production rates for the various reactions are calculated for a future Tau Charm Factory (TCF). With a design luminosity of 10^{33} cm^{-2}s^{-1}, the TCF will produce 10^9 ψ or $5\text{x}10^8$ ψ' events during one month of data accumulation. Detailed

Monte Carlo studies are used to estimate the detection efficiency for various reactions at the TCF. Some detector requirements necessary to accomplish the physics goals are outlined.

2. Inclusive ψ and ψ' radiative charm decays.

The $\psi \to \gamma\eta_c$ decay is an M1 "allowed" process. A nonrelativistic formula for this transition gives[1]:

$$\Gamma(\psi \to \gamma\eta_c) = \frac{16}{27} k^3 \alpha \left(\frac{0.9}{m_c}\right)^2,$$

where k is the energy of the radiative photon and m_c the mass of the c quark. Present experimental results come from the Crystal Ball collaboration, who measured the branching ratio of $\psi \to \gamma\eta_c$ to be $(1.27 \pm 0.36)\%$[2], while corrections to the nonrelativistic formula predict 2.9%[3]. The background in the Crystal Ball measurement comes mainly from overlapping showers from π°'s and from minimum ionizing particles which were not identified in the tracking chamber. Since radiative ψ decay is the largest source of η_c events, a better $\psi \to \gamma\eta_c$ measurement will contribute to smaller errors on measurements of hadronic η_c decays.

With 10^9 TCF produced ψ events one has an inclusive sample of 10^7 η_c events! The 115 MeV radiative photon lies over a large background that includes a π° in the final state, such as $\psi \to \pi^\circ 2(\pi^+\pi^-)$, $\psi \to \pi^\circ 3(\pi^+\pi^-)$, etc. An excellent photon energy resolution will enable subtraction of the π° background. Figure 2 shows a TCF Monte Carlo simulation of the energy of the radiative photon coming from $\psi \to \gamma\eta_c$. An electromagnetic calorimeter resolution of $\sigma(E)/E = 2\%/\sqrt{E}$ was assumed. The background is $E(\gamma)$ of the highest energy photon from $\psi \to \pi^\circ 2(\pi^+\pi^-)$, this decay being the largest π° background. Other $\psi \to \pi^\circ X$ decays show similar $E(\gamma)$ distributions. Good π° reconstruction and good tracking efficiency for all charged tracks in the TCF detector will be essential in suppressing the backgrounds observed by Crystal Ball.

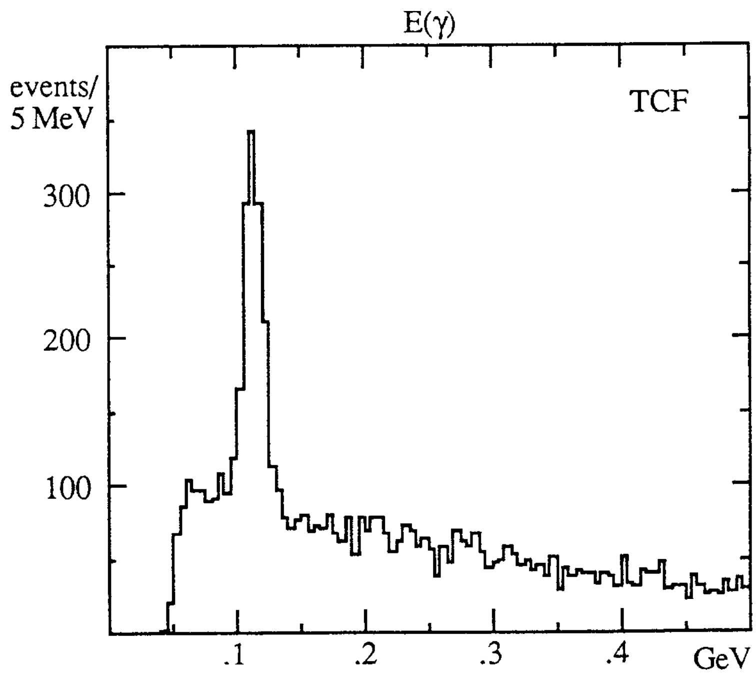

Figure 2: $E(\gamma)$ for $\psi \to \gamma\eta_c$ and the background from $\psi \to \pi^\circ 2(\pi^+\pi^-)$.

Crystal Ball obtained a 95% confidence interval for the branching ratio of radiative ψ' decay into η_c' of (0.2-1.3)%[4]. This is the only observation of the η_c' which has not been measured in any exclusive final state! With a sample of 5×10^8 ψ' events both the absolute branching ratio of radiative ψ' decay into η_c' and some hadronic final states should be accessible. From angular distributions in hadronic η_c' decays its spin and parity could be determined, in a similar way to the $\eta_c \to \phi\phi$ analysis by Mark III[5].

3. The Natural Linewidths of the η_c and η_c'.

The η_c decays mainly into hadrons, through two gluons. Therefore the natural linewidth of the η_c is essentially equal to the η_c hadronic width. Among the earliest predictions of QCD were the hadronic widths of charmonium states. In lowest order calculation the two gluon width of the η_c is:

$$\Gamma(\eta_c \to gg) = \frac{8}{3}\left(\frac{\alpha_s}{m_c}\right)^2 |R(0)|^2,$$

where R(0) is the wave function at the origin[6]. The best measurement for the η_c linewidth comes from Crystal Ball[2] who fitted the width of the radiative photon in $\psi \to \gamma\eta_c$ and obtained a result of (11.5±4.5) MeV. In a subsequent Mark III experiment the $\eta_c \to \bar{p}p$ width was measured, with a large statistical error coming from the small data sample[7].

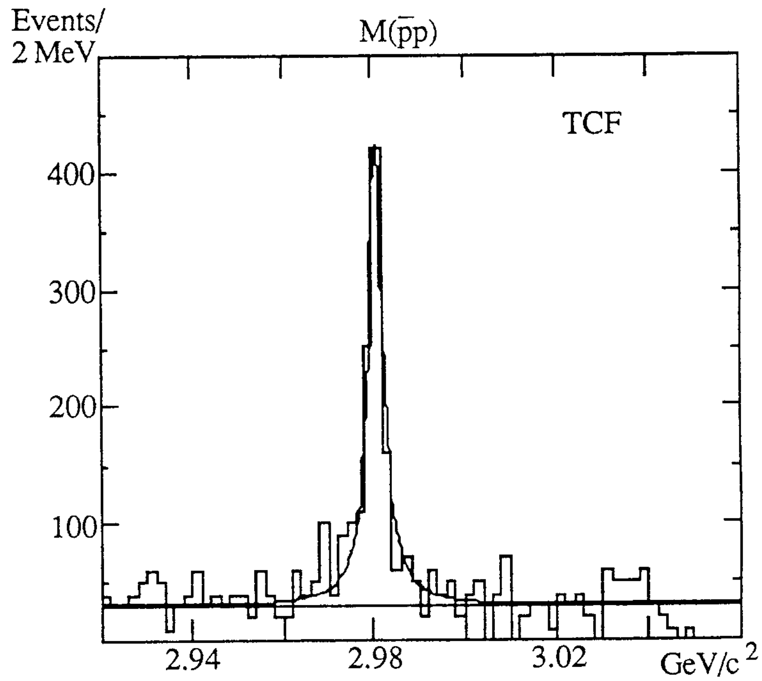

Figure 3: M($\bar{p}p$) for $\psi \to \gamma\eta_c \to \gamma\bar{p}p$

At the TCF with 10^7 η_c events we expect 10^4 $\eta_c \to \bar{p}p$ and 3×10^4 $\eta_c \to \phi\phi$ events. By fitting the $\bar{p}p$ or $\phi\phi$ lineshape we can obtain a $\Gamma(\eta_c)$ measurement with an error of less than 10%! The M($\bar{p}$p) coming from $\psi \to \gamma\eta_c \to \gamma\bar{p}p$ is shown in Figure 3. The background comes from $\psi \to \gamma\bar{p}p$ phase space, and contributes a 12% error to the number of $\eta_c \to \bar{p}p$ events. The background from misidentified pions/kaons is assumed to be small.

No hadronic branching ratios of the η_c' have been measured yet. With (1-6.5)x10^6 produced η_c' events, several hadronic modes would be accessible. A determination of the natural linewidth of the η_c' will be carried out in a similar technique to the η_c measurement.

4. The Two Photon Widths of the η_c and η_c'.

The quark model may be used to predict the $\gamma\gamma$ width of the η_c. With the assumptions that the ψ and the η_c have the same wave function at the origin and that $m_\psi \approx 2m_c$ one obtains to first order in QCD:

$$\Gamma(\eta_c \to \gamma\gamma) = \frac{16}{3}\left(\frac{\alpha}{m_c}\right)^2 |R(0)|^2 \approx \frac{4}{3}\Gamma(\psi \to e^+e^-)\left(1+1.96\,\frac{\alpha_s}{\pi}\right) \approx 7 \text{ keV}.$$

Corrections have been applied to account for relativistic effects[8-10], QCD corrections[10,11], gluon condensates[11] and changes in the wave function due to spin-dependant forces[8] or hyper-fine mass splitting[12]. The results are in a confused state, changing the simple model prediction in both directions, and span the region of $\Gamma_{\gamma\gamma}(\eta_c) \approx$ 3-15 keV.

There have been many experimental measurements of the two photon width of the η_c[13] with the latest coming from the CLEO experiment[14]. The world average is $\Gamma(\eta_c \to \gamma\gamma)$=8.0±2.2 keV. All current measurements depend on the hadronic branching ratios for the η_c, which have large statistical errors, caused by combining Mark III or DM2 $B(\psi \to \gamma\eta_c \to \gamma$ hadrons) measurements, together with the inclusive $\psi \to \gamma\eta_c$ rate from Crystal Ball.

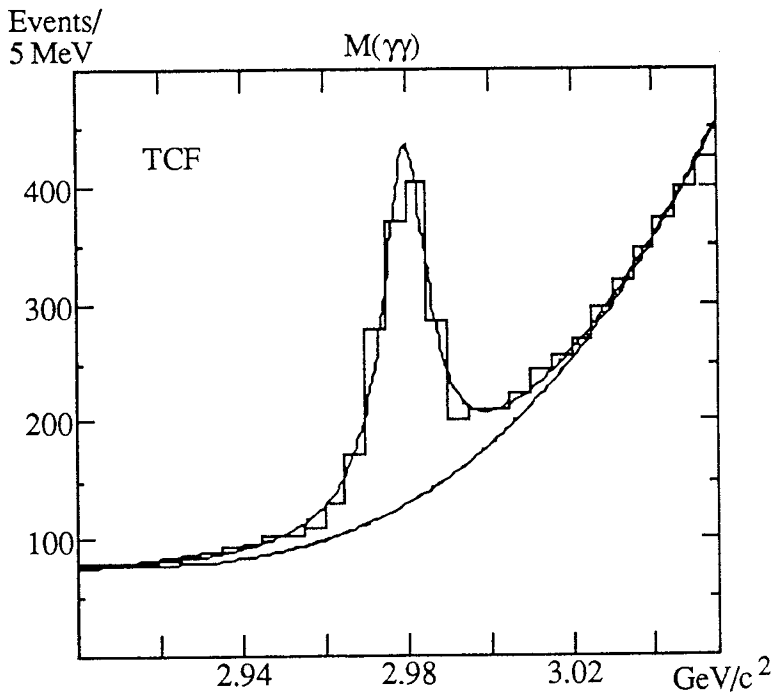

Figure 4: M(γγ) for $\psi \to \gamma\eta_c$, $\eta_c \to \gamma\gamma$ and the QED background.

At the TCF we expect ~10^4 produced $\eta_c \to \gamma\gamma$ events during a month of ψ data taking. A major background is the decay $\psi \to \gamma\eta \to \gamma\gamma\gamma$ where one of the photons from the η decay is equal in energy to the radiative $\psi \to \gamma\eta_c$ photon. Monte Carlo studies show that removing this background halves the detection efficiency to ~45%. Unfortunately, another large background from the QED process $e^+e^-\to\gamma\gamma\gamma$ peaks at the ψ and therefore good photon resolution is crucial in separating the two reactions. Figure 4 shows the mass of the two highest energy photons coming from $\psi\to\gamma\eta_c\to\gamma\gamma\gamma$ and the $e^+e^-\to\gamma\gamma\gamma$ background. An electromagnetic calorimeter resolution of $\sigma(E)/E=2\%/\sqrt{E}$ was assumed. A fit to the distribution in Figure 4 yields an 8% error on the number of $\eta_c\to\gamma\gamma$ events, due to the background determination.

To date no exclusive decay of the η_c' has been observed. It should be possible to measure the $\eta_c'\to\gamma\gamma$ decay rate. Also here the excellent photon energy resolution of the TCF will enable us to identify the QED background from $e^+e^-\to\gamma\gamma\gamma$.

5. The Three Photon decay of the ψ.

The decay $\psi\to\gamma\gamma\gamma$ is related to $\psi\to e^+e^-$ by:

$$\frac{\Gamma(\psi\to\gamma\gamma\gamma)}{\Gamma(\psi\to e^+e^-)}=\frac{4\alpha e_q^4(\pi^2-9)}{3\pi}$$

The branching ratio of $\psi\to\gamma\gamma\gamma$ measures the ψ wave function at the origin and is predicted to be around $2\times10^{-5}\%$[15]. Crystal Ball obtained an upper limit of 5.5×10^{-5} (90% C.L.) due to the QED background $e^+e^-\to\gamma\gamma\gamma$ peaking at the ψ mass. At the TCF we expect 2×10^4 produced $\psi\to\gamma\gamma\gamma$ events but also a large QED background. It might be better to measure $B(\psi\to\gamma\gamma\gamma)$ from the ~3000 produced $\psi'\to\pi^+\pi^-\psi\to\pi^+\pi^-\gamma\gamma\gamma$ events, where there is no QED background.

6. Hadronic η_c and χ decays.

The η_c hadronic decays proceed (in lowest order) through two gluons, while the ψ hadronic decays proceed mainly through three gluons or one virtual photon. A complete set of measurements of η_c decays into two meson nonets (Vector-Vector, Tensor-Tensor, Scalar-Pseudoscalar) can shed light on SU(3) quark model relations and can be compared to hadronic ψ decays (like the Mark III $\psi\to$VP analysis[16]). The $\eta_c\to$SP decays are unique, as ψ or ψ' decays to SP pairs are forbidden.

Several $\eta_c\to$VV decays have been measured by Mark III and DM2, with large experimental errors. A first measurement of $\eta_c\to$TT was recently reported[17], and indications of $\eta_c\to$SP are seen in the Mark III data.

With the TCF one can obtain a huge data sample of η_c and χ events. A month of running at the ψ' will produce 1.4×10^6 η_c, $1\text{-}6.5\times10^6$ η_c', 4.6×10^7 χ_0, 4.4×10^7 χ_1, and 3.9×10^7 χ_2 events. Thus the TCF can be viewed as an "η_c/χ Factory" whose data is used to study many hadronic decays of the η_c and χ states, as well as the $\gamma\gamma$ widths of the χ states.

7. Summary.

A TCF operating at (or close to) the design luminosity of 10^{33} $cm^{-2}s^{-1}$ will provide us with large data samples for the study of charm spectroscopy, SU(3) quark model predictions, and tests of QCD. The present experimental results, theoretical predictions, and TCF projections are summarized in Table 1 below:

Table 1: Charmonium rates.

Reaction	World detected events	Experiment. Rate or Branching Ratio	Theoretical Prediction	TCF produced events	TCF Efficiency
$\psi\rightarrow\gamma\eta_c$	$3x10^4$	(1.27±0.36)%	2.9%	10^7	.75
$\eta_c\rightarrow\gamma\gamma$	150	(8.0±2.2)keV	3-15 keV	$10^4(\psi);10^3(\psi')$	.45 (ψ)
$\eta_c\rightarrow\bar{p}p$	15	(0.10±0.02)%	0.2%	10^4	.60
$\psi\rightarrow\gamma\gamma\gamma$	none	$<5x10^{-5}$ (90%C.L.)	$5x10^{-5}$	$2x10^4(\psi);3x10^3(\psi')$	.85 (ψ')
$\psi'\rightarrow\gamma\eta_c$	$5x10^3$	(0.28±0.06)%	0.83%	$1.4x10^6$	.75
$\psi'\rightarrow\gamma\eta_c'$	$0.3\text{-}2.3x10^4$	(0.2-1.3)%	3.5%	$(1.0\text{-}6.5)x10^6$	.75
$\psi'\rightarrow\gamma\chi_0$	$2.3x10^5$	(9.3±0.8)%	6.6%	$4.6x10^7$	.75
$\psi'\rightarrow\gamma\chi_1$	$1.9x10^5$	(8.7±0.8)%	9.4%	$4.4x10^7$	.75
$\psi'\rightarrow\gamma\chi_2$	$1.7x10^5$	(7.8±0.8)%	9.1%	$3.9x10^7$	.75
$\eta_c'\rightarrow\gamma\gamma$	none	-	4.6 keV	$(0.4\text{-}3.0)x10^3$	.45

Some of the questions not addressed here may be found in other parts of the Tau Charm Workshop Proceedings.

I wish to thank T. Burnett, U. Karshon, A. Seiden, and W. Toki for useful and stimulating discussions, M. Wang for help with the Monte Carlo programs, and the Stanford Linear Accelerator Center for their hospitality.

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*) Supported by the National Science Foundation.

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