# $J/\psi$ and Charmonium Physics in a Tau Charm Factory*

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**Abstract**

A high luminosity Tau Charm Factory will yield a sample of $10^9$ $J/\psi$ and $.5\times10^9$ $\psi'$ produced events per month of running. This represents an enormous increase over previous data samples. In this paper the physics of glueballs, charmonium decays, meson spectroscopy, and rare decays of the $J/\psi$ and $\psi'$ that are possible with this data are discussed.

## INTRODUCTION

Tau Charm Factories designed to have luminosities of $1.0\times10^{33}$ cm$^{-2}$ sec$^{-1}$ will provide enormous numbers of $J/\psi$ and $\psi'$ events in a few months of running. Such large samples will enable searches for gluonium bound states,[1] precision tests of charmonium[2] and even the possibility of observing weak decays of the $J/\psi$. In this paper these possibilities are explored. We first begin with a discussion of current data sets and detector enhancements that will enable a major improvement in physics capabilities and finally, we focus the main discussion on the physics topics.

### Current Data Sets

In a Tau Charm Factory, the projected number of produced $J/\psi$ is $1.0\times10^9$ events per month of running and for the $\psi'$ it is $0.5\times10^9$ events per month. This assumes a conservative estimate of a 50% operating efficiency. These numbers of events represent a vast in-

Table 1. J/$\psi$ and $\psi'$ Data

| Data | Experiment | Events |
|---|---|---|
| J/$\psi$ | Mark II | 1.3 m |
| | Crystal Ball | 2.0 m |
| | Mark III | 5.8 m |
| | DM2 | 8.0 m |
| $\psi'$ | Mark II | 1.0 m |
| | Crystal Ball | 1.3 m |
| | Mark III | 0.3 m |

Table 2. BEPC Physics Program

| Year | Program |
|---|---|
| 1989 | Checkout of BES |
| 1990 | J/$\psi$ $1.0\times10^7$ events |
| 1991 | $\psi''$ or $\tau\bar{\tau}$ at 50 $pb^{-1}$ |
| 1992 | 4.05 GeV $\tau\bar{\tau}$ at 50 $pb^{-1}$ |
| 1993 } 1994 } | J/$\psi$ $1.0\times10^8$ events |
| 1995 | 4.6 GeV charm baryons |

crease in the number of events relative to previous experiments and even to the new Beijing machine. The J/$\psi$ and $\psi'$ data sets are listed in the table 1. The Beijing Electron Positron Collider (BEPC) is expected to have approximately 5 times the luminosity of SPEAR. They[3] have collided beams on the J/$\psi$ and have reconstructed events in the Beijing Spectrometer (BES). They have projected the following running schedule shown in table 2. assuming an eventual Tau Charm Factory coming into operation in the mid-1990's.

## Detector Issues

In a detector[4] for a Tau Charm Factory the proposed improvements over previous detectors includes:

- High resolution electromagnetic calorimetry such as crystal CsI.
- Uniform gapless shower counter acceptance and very forward charged tracking
- High resolution drift chamber tracking

These features will provide a significant improvement in detector capabilities for new physics measurements in J/$\psi$ and $\psi'$ physics. The improved electromagnetic calorimeter will enable much better neutral resolution for the detection and reconstruction of multiple photon topologies and inclusive photon measurements. These include radiative decays of the J/$\psi$ and $\psi'$ as well as the reconstruction of states with one or more $\eta$'s or $\pi^0$'s. The uniform acceptance will improve the spin-parity studies of the glueball and hybrid candidates. An important factor in the spin-parity study of these states is the reach of the polar angle acceptance which is usually limited to |cosθ|<0.8 could be extended to 0.95. Finally, very high resolution momentum will improve the mass resolution which will help the search for narrow width resonances with small production rates.

The most stringent demands that the J/ψ and ψ′ running will place on the detector relative to the ψ″ and τ running is the faster trigger rates and the larger number of events required to reconstruct.[5] The trigger rate for the J/ψ is expected to be 1 Khz and the number of events to reconstruct is $1.0\times10^9$ per month of running. For experiments at $e^+e^-$ machines these numbers may seem to be large but from hadron detectors these are manageable numbers of triggers and events. An experiment now taking data and analyzing events is the charm vertexing experiment at FERMILAB, E791, the successor to E691. The trigger rate[6] is 5 Khz and the number of events to reconstruct is $0.5\times10^9$ . These are numbers comparable to what is expected from the J/ψ running. This experiments uses 30 Exobyte cartridges and writes them out every hour. In order to process the data they are using a group of Silicon Graphics processors, which use RISC chips with 20 MIPS a piece, and the experimentalists expect to process these events in a year. Even though the technology is now available, we would expect that by the time a Tau Charm Factory is built the speed of the processing will increase and the cost of these devices will drop much further.

## PHYSICS

### Glueball Studies

The central prediction of QCD lattice gauge theories is the existence of the lowest lying scalar glueball. Predictions[7] have previously centered around a mass of 1 GeV and recently moved up into the 1.5-2 GeV mass region. Also the mass of the tensor glueball is estimated in these theories to be a factor ≅1.5 larger than the scalar glueball mass. The seminal place to search for the scalar glueball is in radiative J/ψ decays where the two gluons could bind to form bound states of glue as shown in Fig. 1. If the scalar really is in the 1.5-2.0 GeV mass region the overlapping resonances will provide much difficulty to untangle or pull out a scalar

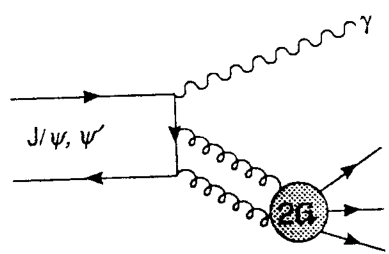

Fig. 1 Radiative J/ψ decay

resonance. The Mark III data on the theta region has been investigated[8] with a moments analysis and due to overlapping resonances the results cannot exclude a scalar underneath a tensor in that region. Another important measurement of a glueball is a complete test of the flavor of the decays by measuring many decay modes. An SU(3) flavor singlet should decay into proper ratios of $\pi\pi$, $\eta\eta$, and $K\bar{K}$. Careful measurements will test this idea and possible form factor corrections.[9]

New breakthroughs in the search for scalar glueballs can only be achieved by looking not only with greater sensitivity but also by use of spin-parity analysis[10] in order to unravel the possibility of overlapping resonances. There have been cases where resonances were lying underneath another resonance of a different spin parity. An example[11] is the $s\bar{s}$ scalar underneath the f′(1525)which could be the real $s\bar{s}$ scalar triplet partner to the f′(1525).

Spin-parity analysis[12] will require very high statistics, uniform acceptance and careful understanding of the backgrounds. The high statistics is easily achievable in a Tau Charm Factory. The uniform acceptance is attained with a gapless barrel shower counter and careful endcap-barrel design. In addition, the very forward acceptance of the drift chamber tracking is very important to test the spin of radiative decays because the polar angle of the radiative photon will depend on the spin. In radiative decays for spin zero the dependence is $1+\cos\theta^2$ and for spin 1 the dependence can be $\sin\theta^2$.

The main decay modes of a scalar glueball are expected to be $J/\psi\to\gamma K^+K^-$, $\gamma K_S K_S$, $\gamma\pi^+\pi^-$, $\gamma\pi^\circ\pi^\circ$, $\gamma\eta\eta$, $\gamma\eta\eta'$. The $J/\psi\to\gamma K^+K^-$ mode has the f′(1525), the θ(1700), and the ξ(2.2) resonances. These decays are affected by feed down from the background of $J/\psi\to K^*K$. This could be substantially reduced by an improved neutral shower detector in order to detect the photons from the $\pi^\circ$ and veto the event. The $J/\psi\to\gamma K_S K_S$ mode is cleaner than the charged mode since the mode $J/\psi\to\pi^\circ K_S K_S$ is forbidden by C parity, however, this mode suffers from small branching ratios and small reconstruction efficiencies. The $J/\psi\to\gamma\pi^+\pi^-$ mode has possible evidence for the $\theta\to\pi^+\pi^-$ but the signal sits on top of the background from $J/\psi\to\rho\pi$. This background could be reduced by use of better shower detection to detect the $\pi^\circ$ decays in order to reject the backgrounds. The totally neutral mode $J/\psi\to\gamma\eta\eta$ provided the first evidence for the θ(1700) resonance and its spin parity. This mode could be easily measured in a fine grained crystal calorimeter in the totally neutral mode where both η's decay into photons. This can be considerably improved with better resolution in the shower counter. In summary, further progress in this measurement will be made by having :

- Significant increases in J/ψ data samples
- Uniform neutral and charged track acceptance
- Improved neutral detector resolution

## Charmonium and $\eta_c$ Studies

Charmonium spectroscopy of the radiative transitions of the $\chi$ states has provided remarkable proof of the quark model. The evidence is a simple picture of atomic spectroscopy of fractionally charged quarks radiating while orbiting in a non-relativistic potential. Combined with the OZI rule and gluon decays from QCD, the charmonium model furnished a clear cut and well defined picture of all strong hadronic decays mesons and baryons. All of these major successes however provide impetus to perform further precise tests and especially to focus on the puzzles which are very striking when viewed or contrasted against the triumphs of the model. These detailed measurements and puzzles include:[13]

- Measurement of the $\eta_c$ two photon width
- Measurement of the J/ψ three photon width and the inclusive photon spectrum
- Precision measurement of the absolute branching ratios of the J/ψ and $\eta_c$ such as $J/\psi \to e^+e^-, \mu^+\mu^-$ and $\eta_c \to p\bar{p}$
- Study of the ψ′ hadronic decay puzzle

The measurements of the two and three photon widths of the $\eta_c$ and the J/ψ are direct tests of the charmonium model. The branching ratios are basically the two and three photon Feynman diagrams divided by the total width. The measurements of the two photon width of the $\eta_c$ have been performed by two photon production experiments from PEP, PETRA and CLEO. The results vary widely and also depend on the poorly measured absolute branching ratios from Mark III and DM2. The three photon width of the J/ψ has not been measured yet.

The measurement of the inclusive photon spectrum from the J/ψ is an important test of QCD. It has been measured by Mark II and these results have approximate agreement with predictions. The Crystal Ball attempted this measurement but could not make the complicated background corrections.

The precision measurement of various $\eta_c$ and J/ψ branching ratios will be useful to normalize results of other experiments that will use the branching ratios of these decays in their product branching ratios. For the J/ψ, the leptonic width is known to only 15% and it will be used in many B meson results and charm production studies in hadroproduction. The branching ratios for $\eta_c$ decays into $p\bar{p}$ and $K\bar{K}\pi$ will be needed to normalize its production in gas jet experiments and two photon production.

Hadronic decays of the J/ψ and ψ′ are still very puzzling. The ratio of the hadronic partial widths of the J/ψ and ψ′ scale as the 3 gluon widths which are the ratio of leptonic widths,

$$\frac{B(\psi' \to \text{hadrons})}{B(\psi \to \text{hadrons})} = \frac{\Gamma(\psi' \to ggg)}{\Gamma(\psi \to ggg)} = \frac{\Gamma(\psi' \to e^+e^-)\,\Gamma(\psi)}{\Gamma(\psi \to e^+e^-)\,\Gamma(\psi')} = (12.2 \pm 2.4)\%$$

This ratio is observed for a number of hadronic modes except the vector-pseudoscalar decays. These missing modes include ρπ, K*K, γη and γη′. The ρπ mode of the J/ψ is one of the largest and in this three pion decay mode of the J/ψ there is absolutely no evidence for nonresonant three pion decays nor any ρ′π decays. In contrast there is no evidence in the ψ′ decays for the ρπ mode but only a small amount of non-resonant three pion decays. These detailed features of the hadronic decays of the J/ψ and ψ′ are very mysterious. The problem is not understood to the extent that it is not known whether the puzzle lies in the ψ′ not having the vector pseudoscalar decay or in the J/ψ having the vector pseudoscalar decay. Most of the hadronic decays of the J/ψ are quasi-two body and relatively few are seen to be non-resonant. In a study[14] of the upsilon ϒ(1s), not a single hadronic mode was found. Apparently at that energy the three gluon annihilation from the $b\bar{b}$ hadronizes into jet fragments and non-resonant multi-pion decays. This indicates that we really do not understand the detailed process of hadronization when three gluons annihilate into hadrons whereas we have a very good understanding of most OZI allowed decays. A most interesting possibility[15] is the existence of a vector glueball that decays into the vector-pseudoscalars and mixes with the J/ψ. If the anomalous behavior is in the J/ψ, which mixes with a vector glueball that causes a large number of quasi-two body modes, the search for this object could be done in three gluon sources such as the two pion decay of the ψ′. This could be performed in the decays ψ′ →ππ+G, η+G, η′+G, where G, the vector glueball, decays into vector pseudoscalar modes. In this double OZI mode, the ψ′ decays into three gluons and three gluons form a vector and the two

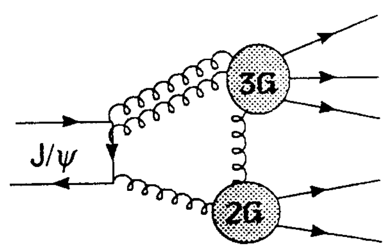


Fig. 2 Double OZI decay

Table 3. Reactions for precise charmonium measurements

| What is detected in J/ψ decays | What is measured |
|---|---|
| (1) J/ψ Inclusive photons | $\int\mathcal{L}dt \times \sigma(e^+e^- \to J/\psi) \times B(J/\psi \to \gamma\eta_c)$ |
| (2) $J/\psi \to \gamma\eta_c$, $\eta_c \to X$ where $X = \gamma\gamma$, $p\bar{p}$, $K\bar{K}\pi$, etc. | $\int\mathcal{L}dt \times \sigma(e^+e^- \to J/\psi) \times B(J/\psi \to \gamma\eta_c) \times B(\eta_c \to X)$ |
| **What is detected in ψ′ decays** | **What is measured** |
| (3) ψ′ Inclusive photons | $\int\mathcal{L}dt \times \sigma(e^+e^- \to \psi') \times B(\psi' \to \gamma\eta_c)$ |
| (4) $\psi' \to \gamma\eta_c$, $\eta_c \to X$ | $\int\mathcal{L}dt \times \sigma(e^+e^- \to \psi') \times B(\psi' \to \gamma\eta_c) \times B(\eta_c \to X)$ |
| (5) Inclusive J/ψ from ψ′ | $\int\mathcal{L}dt \times \sigma(e^+e^- \to \psi') \times B(\psi' \to \pi\pi + J/\psi)$ |
| (6) $\psi' \to \pi\pi + J/\psi$, $J/\psi \to X$ where $X = e^+e^-, \mu^+\mu^-, \gamma\gamma\gamma$ | $\int\mathcal{L}dt \times \sigma(e^+e^- \to \psi') \times B(\psi' \to \pi\pi + J/\psi) \times B(J/\psi \to X)$ |
| (7) $\psi' \to \pi\pi + J/\psi$, $J/\psi \to \gamma\eta_c$, $\eta_c \to X$ | $\int\mathcal{L}dt \times \sigma(e^+e^- \to \psi') \times B(\psi' \to \pi\pi + J/\psi) \times B(J/\psi \to \gamma\eta_c) \times B(\eta_c \to X)$ |

gluons decay into pion pairs, an η or an η′ as shown in Fig. 2. If nothing is seen from the ψ′, the search could be extended to higher $e^+e^-$ energies to allow the possibility of more massive resonances.

The major steps that will improve future measurements include much higher statistics allowing the use of the ψ′ to produce a tagged sample of J/ψ events and a detector with substantially improved neutral detection. A high resolution neutral shower counter will enable an inclusive measurement of the radiative photon spectrum as was done by the Crystal Ball group.

The measurement of the inclusive production rate of the $\eta_c$ and the exclusive modes in the same experiment has a very important advantage in measuring the absolute branching ratios. In the experiments we measure the product branching ratios which equals $\int\mathcal{L}dt \times \sigma(e^+e^- \to J/\psi) \times B(J/\psi \to \gamma\eta_c) \times B(\eta_c \to X)$. Consequently to measure the absolute branching ratio of the $\eta_c$ we need to know the inclusive $\eta_c$ rate from the J/ψ and the production rate of the J/ψ in $e^+e^-$ production. In table 3 we list the possible methods to measure the $\eta_c$ decays into a mode X, which could be into $\gamma\gamma$, $p\bar{p}$, $K\bar{K}\pi$, etc. By measuring both the inclusive and an exclusive mode in J/ψ decays in the reactions (1) and (2) in the table, we can obtain the absolute branching ratios and divide out the luminosity which usually has large uncertainties.

Measuring these modes on the ψ′ has an additional advantage of easily tagging the production of a J/ψ decay by counting the number of events in the $\pi^+\pi^-$ recoil of the J/ψ from the ψ′ for reaction (5). This allows the study of the J/ψ → $e^+e^-$, $\mu^+\mu^-$, γγγ, in reactions (6) by tagging where the precision would otherwise be limited by the luminosity errors. In addition, with the large statistics, reaction (7) could study the radiative transition rate of the J/ψ into the $\eta_c$ and provide a second check.

## OZI decay studies

The OZI rule is the most important operational guideline in strong hadronic decays. Perhaps the most intriguing possibility of a discovery could be made if new resonances would be observed in a very peculiar mode that clearly could not be produced from a conventional $q\bar{q}$ meson decay. These could be the signature of a glueball or a hybrid state. In recent years efforts have been made to search for exotic spin parity resonances, however, the evidence is very tenuous and subject to difficult and often unconvincing spin-parity analyses. Perhaps a better "smoking gun test" could be provided by evidence for a bound state of very unusual combinations of mesons.

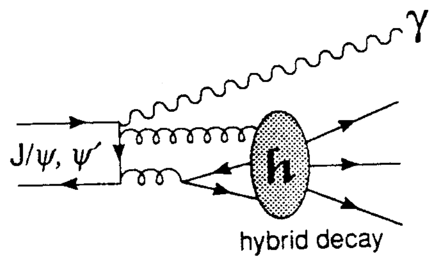


Fig.3 Hybrid Production

Unusual states have been predicted[16] for several hybrid channels. They can be produced in radiative decays as shown in Fig. 3. Among the more unconventional decays are states that will decay into ωK, φω, φK or f′K which are not possible from conventional $q\bar{q}$ mesons. Another source of new states could be 4-quark states.[17] They could be directly pair produced or created in radiative decays where both gluons turn into $q\bar{q}$ pairs as shown in Fig. 4. One puzzle[18] has been the existence of a sizable pseudoscalar resonance produced in radiative J/ψ decays near threshold that decays into a pair of vectors. This may be related, but most 4-

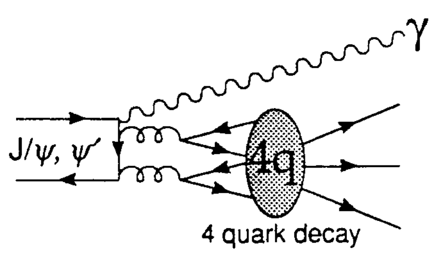


Fig. 4 Four quark decay

quark models do not predict pseudoscalar resonances.[19] Another place to look would be to search[20] for decays with charged hidden strangeness, $s\bar{s}$, such as $\phi\pi^+$, $\eta\pi^+$, $\eta'\pi^+$ and $K^\circ K^+$. These are not possible to produce in the light quark mesons and they would unambiguously signify new physics.

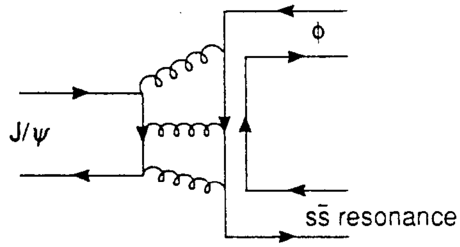


Fig.5 Two body flavor correlated decay of the J/ψ in a φ and a $s\bar{s}$ resonance.

## Meson Spectroscopy

The abundance of flavorless quasi-two body decays of the J/ψ provides a means to study light quark mesons. The two body meson decays are observed[21] in pseudoscalar+vector, tensor+vector, scalar+vector, and axial-vector $(1^{-+})$+pseudoscalar. Although we may not understand the detailed mechanism as to why certain meson pairs are produced and others not, the flavorless three gluon annihilation source forces the pairs of mesons to be quark flavor correlated as shown in Fig. 5. The main examples are $J/\psi \to \omega f, \phi f', S^*\phi, KK^*$ and others. The contrary examples, $J/\psi \to \omega f', \phi f, S^*\omega$, are very suppressed.

These provide a means to produce and study in principle all light quark meson spectroscopy. In addition, unlike $\pi^- p$ and $K^- p$ experiments, there is no t dependence, and the helicity amplitudes are less complicated. The measurements will provide spin-parity tests of mesons, flavor determination and in the case of isoscalars, a mixing angle measurement. They provide a complementary method[22] to the two photon production of mesons and the hadroproduction experiments.

## Rare Decays

Rare decays[23] of the J/ψ and possibly of the ψ′ offer unique low energy tests of the standard model. The very high statistics and the OZI suppression of the J/ψ causing a narrow width may provide the first opportunity of the search for a weak decay of a vector meson. We may estimate the decay by using the life time of the D meson and comparing it to the width of the J/ψ.

$$\frac{2\hbar/\tau(D^\circ)}{\Gamma(J/\psi)} = 5 \times 10^{-7}$$

where we assume a factor of two for two charm quarks and ignore any W exchange which could enhance the decay rate. This would predict roughly 500 decays produced per $10^9$ J/ψ decays. Weak decays of the η and other electromagnetic and strong decaying particles have been estimated[24] and the rates are very small around $10^{-13}$. The search for weak decays could be performed in the following areas:

- Exclusive weak decays of the J/ψ into a charm mesons such as $J/\psi \to D_s\pi$
- C or CP violation decay of the $J/\psi \to \phi\phi$[25] or $K^\circ K^\circ$[26]
- Higgs decays[27] from $J/\psi \to \gamma + H^\circ$, $H^\circ \to \mu\mu$
- Neutral current decays[28] such as $\psi' \to \pi\pi J/\psi$, $J/\psi \to \nu\bar{\nu}$

Exclusive decays of the J/ψ into a charm meson such as the Ds would establish unambigous evidence for weak decays. Thus far there are no examples of a particle that has both weak and strong decays. The weak decay of J/ψ may be the only place for such a measurement as its strong width is relatively narrow due to the OZI suppression. The search for the spectator decay could be done in an inclusive search for the mode $J/\psi \to Ds + X$ or it could be tightly focused on a fully exclusive reaction as shown in Fig. 6. If the reaction includes a semileptonic decay, the missing neutrino and the lepton could provide powerful added requirements that would remove events from regular or conventional three gluon decays of the J/ψ.

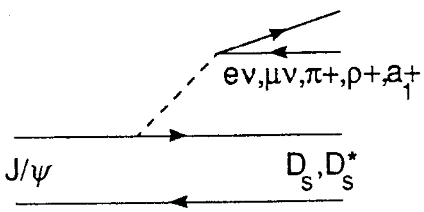

Fig. 6 Weak decay of J/ψ

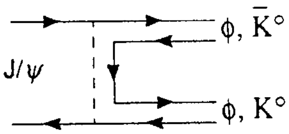

Fig. 7 C and CP violating decay

Other unique decays include C and CP violating decays such as $J/\psi \to \phi\phi$ or $K^\circ K^\circ$ which would occur via the W exchange process as shown in Fig. 7. These decays may be limited by the soft radiative process which would add a photon to conserve C parity. The φφ background yields have been estimated and are small. The estimate for the φφ rate is $10^{-8}$. The $K^\circ K^\circ$ mode has an additional subtlety of testing a form of the Einstein-Rosen-Poldolsky paradox for C conservation. When the J/ψ decays into neutral kaons, the kaons move apart back to back and at some time later, one kaon will decay into a $K_S$ and then the other kaon must only then know that it should be a $K_L$ decay. If EPR is correct there is a short amount of time when the other kaon could choose to decay into a $K_S$. The predicted rate is on the order of $10^{-9}$.

Production of a low mass Higgs boson in radiative J/ψ decays as shown in Fig. 8 is expected at the $10^{-5}$ level in the 2 GeV mass region. The single doublet model will predict the rate once the mass is specified. Although limits have been set by ARGUS and CLEO in B decays, a Higgs could still be emitted from a charm quark if the Higgs coupling is not the same for up and down type quarks. The signal would appear as a narrow peak in the $\mu^+\mu^-$ mass distribution in $J/\psi \to \mu^+\mu^-$ radiative dimuon spectrum. The main background will come from radiative dimuons and the Higgs signal will appear on top of this smooth background. With a sample of $10^9$ J/ψ events a limit of a few times $10^{-7}$ can be obtained in the 2-3 GeV Higgs mass region.

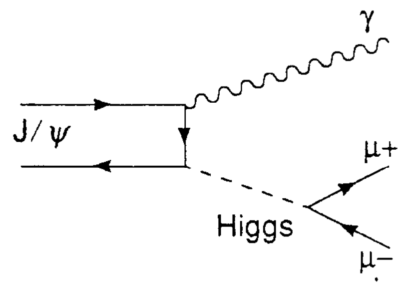


Fig. 8 Higgs decays

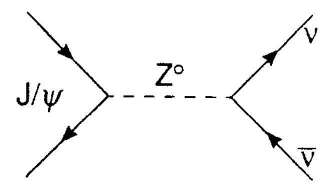


Fig.9 J/ψ neutral current decays

The search for the neutral current decay of the J/ψ as shown in Fig. 9 via the mode, $\psi' \to \pi\pi J/\psi, J/\psi \to \nu\bar{\nu}$ is expected at a very small level, $N_\nu \times 10^{-8}$. If any signal is seen it would be a serious violation of the standard model. The limiting background will be $J/\psi \to n\bar{n}$ which as a branching ratio of .18%. The antineutron should be observable in the hadron calorimeter but some fraction will penetrate the detector or go undetected down the beam pipe.

## SUMMARY

The main physics improvement in the study of J/ψ and ψ′ physics will come about because of:

- Factor of 100-1000 improvement in statistics over previous data samples
- Improved resolution in electromagnetic calorimetry
- Better charged and neutral acceptance

## $J/\psi$ and Charmonium Physics in a Tau Charm Factory

The Tau Charm Factory with with an optimized detector will provide a diverse and topical physics program. The physics topics ( see other papers from the workshop for tau and charm physics which was not covered here ) include:

- Study of gluonium, hybrid and 4-quark resonances
- Precise tests of the charmonium model
- Search for rare decays of the $J/\psi$ and $\psi'$

This physics is uniquely possible at a very high luminosity Tau Charm Factory.

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