Physics at the $\psi(2S)$

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ABSTRACT

The $\psi(2S)$ hides some potentially interesting secrets that could be explored in only a *day*, given the high luminosity of the τcF , and the good acceptance of the proposed detector. I will examine the puzzle of the suppressed hadronic decays to a vector and a pseudoscalar, the as yet unconfirmed h_{c1} and $\eta_c(2S)$ charmonium states, and speculation on the hadronic decays of the χ_{c0}, and examine J/ψ physics that could be done at the ψ'.

1. Introduction

There has not been a serious attempt to take data at the $\psi(2S)$ (formerly known as the ψ' or $\psi(3768)$) for ten years. This is because the only machine and detector capable of running at the ψ', the Mark III at SPEAR, has had only very limited running time, and has chosen to study weak decays of the charmed D and D_s, and to search for non-quark-model mesons in J/ψ decays.

Mark III did collect some ψ' data for calibration purposes in 1982 and 1988, that are now being analyzed. The major data sets, all collected at SPEAR, are summarized in Table I.

TABLE I. Significant $\psi(2S)$ data sets.

Experiment	Events (10^6)
Crystal Ball	1.8
Mark II	1.0
Mark III	0.25

The Mark III detector has superior tracking and photon detection solid angle, and low energy photon efficiency in comparison with Mark II. The Crystal Ball data is limited to analysis of all-neutral and two-charged topologies by its lack of a magnetic field, and it has limited efficiency for multiple tracks and photons due to the shower spreading. The result is that all three data sets are comparable.

The τcF can easily overwhelm the existing world data. Not only could an incredible 10^7 events be obtained in a day's run at 10^{33} luminosity, but the detector design improves the Mark III solid angle and resolution for charged tracks, while matching the Crystal Ball's neutral resolution. In this paper, I will assume an initial exploratory run that obtains 10^7 produced ψ'.

In the next section, I discuss the '$\rho\pi$' puzzle, or the surprising suppression of decays of the type $\psi' \rightarrow$ Vector + Pseudoscalar, compared with the J/ψ. Section 2 is devoted to a discussion of the so-far-unconfirmed charmonium states h_{c1} and $\eta_c(2S)$, and Section 3 covers some speculative ideas about the possibility of detecting exotic mesons in χ decays. The final section covers J/ψ physics accessible from the ψ'.

2. The "$\rho\pi$ Puzzle"

The Mark II data set referred to above was the basis for a remarkable observation[1] that hadronic decays of the ψ' to selected two-body final states seem suppressed with respect to the corresponding J/ψ rates. Since all J/ψ or ψ' decays that do not invoke radiative charmonium transitions are expected to proceed via annihilation of the $c\bar{c}$ quark pair, the amplitude for which is proportional to the wave function at the origin, the rates for J/ψ or ψ' decays to the same final states must all be in the same proportion: if f is any final non-charmonium state,

$$Q_f \equiv \frac{B(\psi' \to f)}{B(J/\psi \to f)} \approx \frac{B(\psi' \to e^+e^-)}{B(J/\psi \to e^+e^-)} = 0.135 \pm 0.023.$$

This expectation is badly violated by the Mark II data,[1] most dramatically by the $\rho\pi$ final state: $Q_{\rho\pi} < 0.0056$. Non-charmonium radiative decays to pseudoscalars seem to similarly suppressed. Table II shows some of the final states that have been measured:

TABLE II. Comparison of J/ψ and ψ' decay branching fractions. (units of 10^{-4})

f	$B(J/\psi \to f)$	$B(\psi' \to f)$	$0.13 * B(\psi \to f)$
e^+e^-	690 ± 90	90 ± 15	90
$p\bar{p}$	22 ± 2	1.9 ± 0.5	2.9
γf_2	14 ± 2	1.3 ± 0.4	1.8
$\rho\pi$	142 ± 19	< 0.8	19
$K^{\pm}K^{\mp *}$	53 ± 5	< 1.5	6
$\gamma\eta'$	43 ± 11	< 2.0	6
$\gamma\iota$	46 ± 7	< 1.2	6

The last column is the expected ψ' branching fractions if the "13%" rule held. Note that the suppression seems to apply only to vector pseudoscalar final states, where the vector may be a photon. That is, the $p\bar{p}$ and γf_2 modes does not seem to be affected.

Because of the crisply defined nature of this puzzle, there have been a number of theoretical attempts to explain it. Hou and Soni[2] first suggested that the explanation was that a vector glueball, which couples strongly to vector-pseudoscalar final states, but not to e^+e^-, was enhancing the rate at the J/ψ since it was located nearby.

Brodsky, Lepage, and Tuan[3] refined this notion with the observation that vector-pseudoscalar final states are suppressed by the QCD theorem for ψ decays, but not for decays of the glueball. They calculated that the glueball must in fact lie within 80 MeV of the J/ψ. A difficulty for this hypothesis is that radiative decays, like $\gamma\eta'$, show the same pattern, and indeed the decay $J/\psi \rightarrow \omega\pi^\circ$ indicates the presense of an electromagnetic amplitude that is about 10% of the hadronic one. Helicity conservation, the basis for the QCD Theorem, would also suppress electromagnetic amplitudes, which a nearby glueball is unlikely to enhance.

Another model that can also account for the electomagetic decays is that of Chaichian and Törnqvist[4] who propose that the effect is simply due to form factors. They expect an additional suppression factor for all "pre-asymptotic" two-body decay modes of ≈ 55, due to the higher momentum for the ψ' decay products. They then predict $B(\psi' \rightarrow \rho\pi) = 0.35 \times 10^{-4}$ if the amplitude is purely hadronic, or 0.70×10^{-4} with a more refined calculation including an electromagnetic component.

A final model is due to Pinsky[5] , who relates the decays $J/\psi \rightarrow$ PV and $\psi' \rightarrow$ PV to $J/\psi \rightarrow \gamma\eta_c$ and $\psi' \rightarrow \gamma\eta_c$, respectively, and observes that the latter is a hindered M1 transition. This model predicts $B(\psi' \rightarrow \rho\pi) = 0.68 \times 10^{-5}$.

A preliminary analysis of the Mark III data[6] results in a limit slightly below the Mark II one quoted in Table II.

The objective of an analysis to sort this all out would be to measure all the PV branching fractions, which would allow an analysis similar to that done at the J/ψ. An important objective would be to measure the electromagnetic amplitude, for example by measuring $\omega\pi$, and other two body modes, like ωf_2. There are different predictions for these last two. The nominal 10^7 data sample, with 50% reconstruction efficiency, corresponds to a branching fraction sensitivity of 4×10^{-7}. This is well below any of the predictions for $\rho\pi$, or the expectations from J/ψ decays, with or without formfactors, for any of the final states of interest.

3. Confirmation of the h_{c1} and $\eta_c(2S)$

It is remarkable that two of the low-lying charmonium states are still unconfirmed, although there is evidence for both. Unless a very unexpected failure of the charmonium model occurs, both should be easily confirmed with our nominal day's run. I discuss each briefly:

3.1. $\eta_c(2S)$

The Crystal Ball found[7] a significant signal in inclusive ψ' radiative decays for a state at the mass expected for the $\eta_c(2S)$, with a branching fraction

$$B(\psi' \to \gamma\eta_c(2S)) = (0.75 \pm 0.55)\%.$$

With 10^7 ψ' this would correspond to $75K$ produced. With similar photon resolution to the Crystal Ball, the τcF would of course confirm the specific signal easily. We would of course look for specific decay modes as well. An important objective would be to determine the spin-parity. If the branching fraction to $\phi\phi$ were the same as for the η_c, 3.4×10^{-4}, and assuming a reasonable efficiency of 60%, we would have 150 events. Recall that the Mark III determination[8] of the spin-parity of the η_c was accomplished with only 20 events!

3.2. THE h_{c1}

The h_{c1} is the singlet-P state. Its mass should be at the center of gravity of the triplet-P states, 3525 GeV. Its J^{PC} is 1^{+-}: C invariance forbids a single photon transition from the C-odd ψ', and it has the wrong parity to be produced directly. Thus it is difficult to see at an e^+e^- machine, and indeed no such evidence for it exists.

The ISR experiment R704[9] studied $\bar{p}p \rightarrow J/\psi X$, and found a 2.3σ signal with a fitted mass in agreement with the prediction. A follow-on experiment at Fermilab, E-760, which uses the Antiproton Accumulator Ring, will undoubtedly confirm this state (if it exists) soon.

Studies using the τcF have the advantage of being able to study a variety of final states, and the possibility of determining the spin and parity. The most likely production mechanism is $\psi' \rightarrow \pi^\circ h_c$. This is of course suppressed by isospin. A 95% CL upper limit from the Crystal Ball for this is 0.8% in the mass region of interest. The h_c can decay by single photon amazon to the η_c. The limit from the Crystal Ball for the cascade $\psi' \rightarrow \pi^\circ h_c, h_c \rightarrow \gamma\eta_c$ is 0.16%. Although this is expected to be the largest mode, the R704 result indicates that the $\bar{p}p$ mode must exist: this would be quite easy to detect.

A Monte Carlo study by the Mark III group[10], concluded that with the Mark III detector, and a data set of $3.9 \times 10^6 \psi'$'s, that it should be possible to detect this state.

4. Hadronic decays of the χ_c States

Very little is known about the hadronic decays of the χ states. Our 10^7 data set would contain over half a million each. Close has suggested[11] that since the χ_0 may decay into two scalars, one may see interesting structure in the 2π mass distributions of the 4π final state.

Another interesting possibility is afforded by the χ_1: since it has even charge conjugation, odd-C final states are accessible to radiative decays. Like the J/ψ, the system recoiling from such a photon should have an enriched two-qluon content. So this may be a place to look for odd-C glueballs.

5. J/ψ physics at the ψ'

The ψ' is a copious source of J/ψ decays: the branching fraction for $\psi' \to \pi\pi J/\psi$ is 50%. (These decays in fact represent a difficult background for some direct decays.) Does this represent an opportunity to study the physics of J/ψ decays? There appear to be three possibilities: absolute branching fractions with low systematics, the possibility to look for decays to neutral weakly interactive final states, and performing spin-parity analyses with a different acceptance and thus different systematic errors.

5.1. Precise J/ψ branching ratios

It is difficult to measure J/ψ branching fractions to better than 10%, while running at the J/ψ. That is, such measurements tend to be limited by systematics involved in determining the total number of produced J/ψ. The ψ', however, produces J/ψ's with a nice 2π tag that is independent of the J/ψ decay mode. A fundamental decay that has implications for the value of α_s at the charm mass scale is $J/\psi \to \mu\mu$, which is now known only to 15%, although Mark III should improve this. A much better measurement of this mode would allow better normalization of a J/ψ data set, through comparison with the $\mu\mu$ final state.

5.2. J/ψ decays to neutrinos *et al.*

The rate for $J/\psi \to \nu\bar{\nu}$ is proportional to the number of neutrino generations. The standard model branching fraction is[12] $\approx 7 \times 10^{-9}$. We cannot hope to approach this level, even if we did collect 10^9 ψ''s. The reasons are two-fold: hermiticity at this level is very hard to achieve, and is not a primary detector design goal. But more fundamentally, such a measurement would have to contend with the decay $J/\psi \to n\bar{n}$, which has a branching fraction of $\approx 2 \times 10^{-3}$. Thus if the probability that a neutron did not interact in the muon detectors was 1%, a reasonable number, this background would still be 100 times the signal.

Of course, one should look for this mode anyway: even though the standard model prediction is unattainable, a SUSY surprise could be lurking. With 10^7 produced ψ', we would be sensitive to $\approx 10^{-6}$, which is the $n\bar{n}$ limit.

5.3. SPIN-PARITY ANALYSIS OF J/ψ DECAYS

A major objective of the τcF will be to resolve the confusion remaining from previous spin-parity analyses, particularly the radiative decays to $K\bar{K}\pi$ and $\eta\pi\pi$ final states. This is probably best done running at the J/ψ itself. A very important angle for such analyses is the direction of the radiative photon. Unfortunately this is cut off by the finite detector acceptance, which reduces the sensitivity, and is a source of systematic error. At the ψ', this angle is no longer correlated as strongly with the laboratory system. Thus if sufficient ψ' data were available (probably meaning more than 10^7), we could check J/ψ results with different systematics.

6. Conclusions

I conclude that given the high luminosity of the τcF , and the relatively unexplored status of the ψ', that a number of interesting experimental questions can be explored with very little impact on the rest of the program.

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