PHYSICS IN CHARM ENERGY REGION

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ABSTRACT

Recent results on physics in the charm energy region are reviewed. Theoretical puzzles related to the exclusive hadronic decays of $J/\psi$ and $\psi'$ are analyzed. New results and issues on possible glueball candidates such as $\xi(2230), \eta(1440)$ and $f_0(1500)$ observed in $J/\psi$ radiative decays and other experiments are emphasized. Problems in charmonium production with large transverse momentum at the Tevatron and fragmentation mechanisms of quarks and gluons, and in particular the $\psi'$ surplus and color-octet fragmentation are discussed. Some theoretical and experimental results in charmonium and open charm hadrons are also reported.

I. Introduction

Physics in the charm energy region is in the boundary domain between perturbative and nonperturbative QCD. The study of charmonium physics has recently received renewed interest. The observed hadronic decays of charmonium may give new challenges to the present theoretical understanding of the decay mechanisms. More glueball candidates are observed in charmonium radiative decays, and are arousing new studies of glueball physics. The observed prompt production of charmonium at the Tevatron and the serious disagreement between expected and measured production cross sections have led to new theoretical speculations about charmonium spectrum and novel production mechanisms. There are also many new results in open charm physics, including new measurements of charmed meson and baryon decays. In this report some of the new results and the status of theoretical studies of physics in the charm energy region will be reviewed.

II. Problems in Charmonium Hadronic Decays

Charmonium hadronic decays may provide useful information on understanding the nature of quark-gluon interactions and decay mechanisms. They are essentially re-
lated to both perturbative and nonperturbative QCD. The mechanism for exclusive hadronic decays is still poorly understood. One of the striking observations is the so-called “ρπ” puzzle, i.e., in the decays of J/ψ and ψ′ into ρπ and K∗K the branching ratios of ψ′ are greatly suppressed relative to that of J/ψ [1]. New data from BES not only confirmed this observation but also found some new suppressions in the ωf2 and ρa2 channels [2][3]. This gives a new challenge to the theory of charmonium hadronic decays.

Because for any exclusive hadronic channel h the decay proceeds via the wave function at the origin of the cc bound state, one may expect

\[ Q_h \equiv \frac{B(\psi' \to h)}{B(J/\psi \to h)} \approx \frac{B(\psi' \to 3g)}{B(J/\psi \to 3g)} \approx \frac{B(\psi' \to e^+e^-)}{B(J/\psi \to e^+e^-)} \approx 0.14. \]  (1)

Most channels like 3(π+−π−)π0, 2(π+−π−)π0, (π+−π−)pπ0, π0pπ, 2(π+−), and the newly measured pπ, ΛΛ, Σ0Σ0, ξ−Ξ− by BES seem to approximately respect this relation. But \( Q_h \) for ρπ and K∗K were found (and confirmed by BES) to be smaller by more than an order of magnitude than the normal value 0.14. The new BES data give [2][3]

\[ Q_{\rho\pi} < 0.0028, \quad Q_{K^{*\pm}K^{\mp}} < 0.0048. \]  (2)

This puzzle has led to some theoretical speculations.

The Hadron Helicity Conservation theorem in QCD [4], suggested by Brodsky and Lepage, indicates that because vector-gluon coupling conserves quark helicity for massless quarks, and each hadron’s helicity is the sum of the helicity of its valence quarks, in hard process the total hadronic helicity is conserved (up to corrections of order \( m/Q \) or higher)

\[ \sum_{\text{initial}} \lambda_H = \sum_{\text{final}} \lambda_H. \]  (3)

According to this theorem the decays of J/ψ and ψ′ → VP (vector and pseudoscalar such as ρπ and K∗K) are forbidden. This seems to be true for ψ′ but not for J/ψ. The anomalous abundance of VP states in J/ψ decay then needs an explanation.

In this connection one possible solution to the ρπ puzzle is the J/ψ − O mixing models [5][6][7]. These models, though slightly different from each other, have the same essence that the enhancement of J/ψ → ρπ, K∗K is due to O → ρπ, K∗K, where O could be a Pomeron daughter [5] or a vector glueball [6][7], which could lie in the region close to J/ψ mass and then mixed with J/ψ but not ψ′.

It has been suggested to search for this vector glueball in processes J/ψ, ψ′ → (η, η', ππ) + O, followed by O → ρπ, K∗K. Obviously, the J/ψ − O mixing model depends heavily on the existence of a vector glueball near the J/ψ. It is therefore crucial to search for it in the vicinity of J/ψ. But so far there seem no signs for it.
Another proposed solution to this puzzle is the so-called generalized hindered M1 transition model \[^8\]. It is argued that because \(J/\psi \rightarrow \eta_c \gamma\) is an allowed M1 transition while \(\psi' \rightarrow \eta_c \gamma\) is hindered (in the nonrelativistic limit), using the vector-dominance model to relate \(\psi' \rightarrow \gamma \eta_c\) to \(\psi' \rightarrow \psi \eta_c\) one could find the coupling \(G_{\psi'\psi\eta_c}\) is much smaller than \(G_{\psi \psi \eta_c}\), and then by analogy, the coupling \(G_{\omega' \rho \pi}\) would be much smaller than \(G_{\omega \rho \pi}\). Assuming \(\psi' \rightarrow \rho \pi\) to proceed via \(\psi' \rightarrow \omega'\) mixing, while \(\psi \rightarrow \rho \pi\) via \(\psi \rightarrow \omega\) mixing, one would find that \(\psi' \rightarrow \rho \pi\) is much more severely suppressed than \(\psi \rightarrow \rho \pi\).

There is another model \[^9\] in which a hadronic form factor is introduced to exponentially decrease the two meson decays of \(\psi'\) relative to \(J/\psi\). But this model predicts a large suppression for many two meson modes, which may not be compatible with the present data. There is also a proposal to explain this puzzle based on the mechanism of sequential quark pair creation \[^10\].

Now the new BES data give a new challenge to these speculations. It is found that in addition to \(\rho \pi\) and \(K^*K\) the suppression also exists in the VT (vector-tensor) channels of \(\psi'\) decays such as \(\psi' \rightarrow \omega f_2(1270)\) \[^2\] \[^3\].

\[ Q_{\omega f_2} < 0.022, \]  

(4)

and the preliminary data on \(\rho a_2, K^*K^*, \phi f_2^*\) channels seem to also show suppressions for \(\psi'\), whereas in the \(b^+_1 \pi^\pm\) channel there is no suppression is observed for \(\psi'\).

The VT decays do not violate helicity conservation, therefore the suppression is hard to understand. Moreover, in the \(J/\psi - \mathcal{O}\) mixing model the \(\mathcal{O} \rightarrow VT\) decay is not expected to be a dominant mode, and therefore \(J/\psi \rightarrow VT\) may not be enhanced. Moreover, using the vector dominance model one might relate \(\psi' \rightarrow \omega f_2\) to \(\psi' \rightarrow \gamma f_2\), but the observed \(\psi' \rightarrow \gamma f_2\) is not suppressed\[^{11}\], and this is also confirmed by BES. In the generalized hindered M1 transition model, the coupling \(G_{\omega' \omega f_2}\) for \(\omega' \rightarrow \omega f_2\) should not be suppressed because by analogy the coupling \(G_{\psi' \psi \chi c}\) is not small due to the fact that the E1 transition \(\psi' \rightarrow \gamma \chi c\) is not hindered. Therefore via \(\psi' \rightarrow \omega'\) mixing the \(\psi' \rightarrow \omega' \rightarrow \omega f_2\) decay is expected to be not suppressed. It seems that within the scope of proposed models and speculations the puzzles related to the VP and VT suppressions have not been satisfactorily solved yet.

In order to understand the nature of these puzzles, systematic studies on \(J/\psi\) and \(\psi'\) exclusive hadronic decays are needed. Many different decay channels such as VP (\(\rho \pi, K^*K, \omega \eta, \omega \eta', \phi \eta, \phi \eta', \) and isospin violated \(\omega \pi^0, \rho \eta, \rho \eta', \phi \pi^0, \cdots\)), VT (\(\omega f_2, \rho a_2, \phi f_2, \phi f_2^*, \cdots\)) \(\mathcal{AP}(b_1 \pi, \cdots), \mathcal{TP}(a_2 \pi, \cdots), \mathcal{VS}(\omega f_0, \phi f_0, \cdots), \mathcal{VA}(\phi f_1, \omega f_1, \cdots)\) and three-body or many-body mesonic decays (\(\omega \pi^+ \pi^-, \phi K\bar{K}, \cdots\) and baryonic decays (\(p\bar{p}, n\bar{n}, \Lambda\bar{\Lambda}, \Sigma\bar{\Sigma}, \Xi\bar{\Xi}, \cdots\)) are worth studying and may be helpful to reveal the essence of the puzzle and the nature of decay mechanisms. In addition, to test the hadron helicity conservation theorem, measurements of the decay angular momentum distribution are also important. E.g., it predicts a \(\sin^2 \theta\) distribution for \(J/\psi, \psi' \rightarrow \omega f_2\) \[^2\].
Since the $\eta_c, \eta'_c$ systems are the counterparts of $J/\psi, \psi'$, it has been suggested to study exclusive hadronic decays of $\eta_c$ and $\eta'_c$. It is argued that for any normal hadronic channel $h$, based on the same argument as for $J/\psi$ and $\psi'$, the following relation should hold:

$$P_h \equiv \frac{B(\eta'_c \to h)}{B(\eta_c \to h)} \approx \frac{B(\eta'_c \to 2g)}{B(\eta_c \to 2g)} \approx 1.$$  \hspace{1cm} (5)$$

This relation differs from the “0.14” rule for $J/\psi, \psi'$, because $\eta'_c \to 2g$ is the overwhelmingly dominant decay mode, whereas for $\psi'$ the $\psi' \to J/\psi \pi \pi$ and $\psi' \to \gamma \chi_{cJ}$ ($J = 0, 1, 2$) transitions are dominant. As the “0.14” rule for $J/\psi$ and $\psi'$, this relation for $\eta'_c$ and $\eta_c$ may serve as a criterion to determine whether there exist anomalous suppressions in the $\eta_c, \eta'_c$ systems. As pointed out in [13] that since the observed $\eta_c \to VV (\rho \rho, K^*\bar{K}^*, \phi \phi)$ and $p\bar{p}$ decays, which are forbidden by helicity conservation, seem to be not suppressed, there might be a $0^{+-}$ trigluonium component mixed in the $\eta_c$. It then predicts a severe suppression for these decays of $\eta'_c$, which is not close to and therefore not mixed with the $0^{+-}$ trigluonium. The $\eta_c$ and $\eta'_c$ hadronic decays are being searched for at BES/BEPC, and will be studied at the $\tau$-charm factory in the future. In this connection, it might be interesting to see whether E760-E835 experiment can find $\eta'_c$ in $p\bar{p} \to \eta'_c \to 2\gamma$. If $\eta'_c \to p\bar{p}$ is severely suppressed by helicity conservation, as the counterpart of $\psi' \to \rho \pi \pi$, then it would be hopeless to see $\eta'_c$ in $p\bar{p}$ annihilation. Therefore the E760-E835 experiment will further test helicity conservation and shed light on the extended “$\rho \pi$” puzzle.

On the other hand, the theoretical understanding for these puzzles and, in general, for the nature of exclusive hadronic decay mechanisms is still very limited. It concerns how the $c\bar{c}$ pair convert into gluons and light quarks and, more importantly, how the gluons and quarks hadronize into light hadrons. The hadronization must involve long distance effects and is governed by nonperturbative dynamics. These problems certainly deserve a thorough investigation in terms of both perturbative and nonperturbative QCD.

III. Search for Glueballs in Charmonium Decays

Existence of the non-Abelian gluon field is the key hypothesis of QCD, and observation of glueballs will be the most direct confirmation of the existence of gluon field. Charmonium radiative decays into light hadrons proceed via $c\bar{c} \to \gamma + g + g$ and are then the gluon-rich channels. Therefore, charmonium especially $J/\psi$ radiative decays are very important processes in the search for glueballs. Recent experimental studies indicate that there are at least three possible candidates of glueballs which are related to $J/\psi$ radiative decays.

- $\xi(2230) \quad J^{PC} = (?)^{++}$.

The new data from BES [2] [15] confirmed the Mark III result [16] and found four decay modes of $\xi \to \pi^+\pi^-, K^+\bar{K}^-, K_S\bar{K}_S$, $p\bar{p}$ in $J/\psi \to \gamma \xi$ with a narrow width of
\( \Gamma_\xi \approx 20 \text{ MeV} \). The branching ratios are found to be \( B(J/\psi \to \gamma \xi) \times B(\xi \to X) \approx (5.6, 3.3, 2.7, 1.5) \times 10^{-5} \) respectively for \( X = \pi^+\pi^-, K^+K^-, K_SK_S, pp \).

Combining these data with the PS 185 experiment on \( p\bar{p} \to \xi(2230) \to K\bar{K} \) [17], \( B(\xi \to p\bar{p}) \times B(\xi \to K\bar{K}) < 1.5 \times 10^{-4} \) (for \( J=2 \)) reveals some distinct features of the \( \xi(2230) \): the very narrow partial decay widths to \( \pi\pi \) and \( K\bar{K} \) (less than 1 MeV with branching ratios less than 5%); the large production rate in \( J/\psi \) radiative decays \( (B(J/\psi \to \gamma \xi) > 2 \times 10^{-3}) \); the flavor-symmetric couplings to \( \pi\pi \) and \( K\bar{K} \). These features make \( \xi(2230) \) unlikely to be a \( q\bar{q} \) meson but likely to be a \( J^{PC} = (even)^{++} \) glueball [18][19].

The \( \xi(2230) \) once was interpreted as an \( ss \) meson[20]. But a recent quark model calculation[21] for decays of \( 1^3F_2 \) and \( 1^3F_4 \) \( ss \) mesons shows that the widths of \( 1^3F_2 \) and \( 1^3F_4 \) \( ss \) mesons are larger than 400 MeV and 130 MeV respectively. The partial width of \( 1^3F_4 \) to \( K\bar{K} \) is predicted to be \( (14 \sim 118) \text{MeV} \), also much larger than that of \( \xi(2230) \). Moreover, the lattice study of \( SU(3) \) glueballs by the UKQCD group suggests the mass of \( 2^{++} \) glueball be \( 2270 \pm 100 \text{MeV} \), consistent with the mass of \( \xi(2230) \). But the spin of \( \xi(2230) \) has not been determined yet. \( (J^{PC} = 4^{++} \) will not favor a glueball because it would require a non-\( S \) wave orbital angular momentum between the constituent gluons, and then lead to higher mass and lower production rate in \( J/\psi \) radiative decays than \( \xi(2230) \)). Moreover, in order to see through the nature of \( \xi(2230) \) (e.g., by further examining the flavor-symmetric decays and the difference between glueball and \( q\bar{q}g \) hybrid), more data are needed for other decay modes, such as \( \eta\eta, \eta\eta' \), \( \eta'\eta' \) and \( \pi\pi\pi\pi, \pi\pi K\bar{K}, \rho\rho, K^*\bar{K}^*, \omega\phi, \phi\phi \), etc.

- \( \eta(1440) \), \( J^{PC} = 0^{--} \).

For years this state has been regarded as a good candidate for the \( 0^{--} \) glueball. However, since both Mark III [23] and DM2[24] find three structures (two \( 0^{++} \) and one \( 1^{++} \) in the energy region \( 1400 \sim 1500 \text{MeV} \) in \( J/\psi \to \gamma K\bar{K}\pi \), the status of \( \iota/\eta(1440) \) as a \( 0^{--} \) glueball is somewhat shaky. But the new (preliminary) generalized moment analysis of BES [25], which avoids the complicated coupling effects from different intermediate states \( (K^*\bar{K} \text{ and } a_0\pi) \), indicates that the \( \eta(1440) \), being one of the three structures, may have a larger production rate in \( J/\psi \) radiative decays with \( B(J/\psi \to \gamma\eta(1440)) \cdot B(\eta(1440) \to K\bar{K}\pi) \approx 2 \times 10^{-3} \). This may reinforce the \( \eta(1440) \) being a \( 0^{--} \) glueball candidate.

While more data and analyses are needed to clarify the discrepancies between Mark III, DM2, and BES, some theoretical arguments support \( \iota/\eta(1440) \) being a \( 0^{--} \) glueball. The helicity conservation argument favors \( 0^{--} \) glueball decaying predominantly to \( K\bar{K}\pi \) [26]. Working to lowest order in \( 1/N_c \) and using chiral lagrangians also get the same conclusion [27]. However, the lattice QCD calculation by UKQCD predicts the mass of \( 0^{--} \) glueball to be \( \sim 2300 \text{MeV} \) [22], much higher than 1440 MeV.

- \( f_0(1500) \), \( J^{PC} = 0^{++} \).

The Crystal Barrel (CBAR) Collaboration [28] at LEAR has found \( f_0(1500) \) in
\[ p\bar{p} \rightarrow \pi^0 f_0(1500) \] followed by \[ f_0(1500) \rightarrow \pi^0\eta, \eta\eta' \]. This state might be the same particle as that found by WA91 Collaboration in central production \[ pp \rightarrow pf(2\pi^+2\pi^-)p \], and that found by GAMS in \[ \pi^-p \rightarrow \eta\eta'n, \eta\eta n, 4\pi^0n \], namely, the \( G(1590) \). So far no signals have been seen in \( J/\psi \) radiative decays in channels like \( \pi\pi, \eta\eta, \eta\eta' \) for \( f_0(1500) \). However, it is reported recently that re-analysis of Mark III data on \( J/\psi \rightarrow \gamma(4\pi) \) reveals a resonance with \( J^{PC} = 0^{++} \) at 1505 MeV, which has a strong \( \sigma\sigma \) decay mode [31]. If this result is confirmed, \( f_0(1500) \) may have been seen in three gluon-rich processes, i.e., the \( pp \) annihilation, the central production with double Pomeron exchange, and the \( J/\psi \) radiative decays, and is therefore a good candidate for \( 0^{++} \) glueball. It will be interesting to see whether \( f_0(1500) \to \sigma\sigma \to 4\pi \) is the main decay mode in the CBAR experiment. The mass of \( f_0(1500) \) is consistent with the UKQCD lattice calculation [22].

The theoretical understanding of glueballs is still rather limited. There are different arguments regarding whether glueball decays are flavor-symmetric.

- **Helicity Conservation.**
  It was argued by Chanowitz [28] that although glueballs are \( SU(3) \) flavor singlets it is inadequate to use this as a criterion for identifying them because large \( SU(3) \) breaking may affect their decays. In lowest order perturbation theory the decay amplitude is expected to be proportional to the quark mass

\[ M(gg \to q\bar{q})_{J=0} \propto m_q, \]

so that decays to \( s\bar{s} \) are much stronger than \( u\bar{u}+d\bar{d} \) for \( 0^{++} \) and \( 0^{-+} \) glueballs. This is a consequence of “helicity conservation”- the same reason that \( \Gamma(\pi \to \mu\nu) \gg \Gamma(\pi \to e\nu) \), and this might explain why \( \iota/\eta(1440) \to K\bar{K}\pi \) is dominant.

- **Discoloring of gluons by gluons.**
  It was argued by Gershtein et al. [32] that due to QCD axial anomaly the matrix element \( \alpha_s < 0|G\bar{G}|\eta' > \) gets a large value. Therefore, if the glueball decay proceeds via production of a pair of gluons from the vacuum and recombination of the gluons in the initial state with the produced gluons, then decays into \( \eta' \) will be favored. This may explain why the \( 0^{++} G(1590) \) has a larger decay rate into \( \eta\eta' \) than \( \eta\eta, \pi\pi, KK \).

- **Glueball-\( q\bar{q} \) mixing.**
  It was argued by Amsler and Close [33] that for a pure glueball \( G_0 \) flavor democracy (equal gluon couplings to \( u\bar{u}, d\bar{d} \) and \( s\bar{s} \)) will lead to the relative decay branching ratios \( \pi\pi : K\bar{K} : \eta\eta : \eta\eta' = 3 : 4 : 1 : 0 \). Then by mixing with nearby \( q\bar{q} \) isoscalars the mixed glueball state becomes

\[ |G> = |G_0> + \xi(|u\bar{u}> + |d\bar{d}> + \omega|s\bar{s}>), \]

and the observed decay branching ratios \( \pi\pi : K\bar{K} : \eta\eta : \eta\eta' = 1 : 0.1 : 0.27 : 0.19 \) for \( f_0(1500) \) may be explained in a color flux-tube model with certain values for mixing angles \( \xi \) and \( \omega \) with the nearby \( f_0(1370) \) (an \( u\bar{u}+d\bar{d} \) state) and an \( s\bar{s} \) state in the...
1600 MeV region. The problem for $f_0(1500)$ and $f_0(1710)$ has also been discussed in Ref. [34].

- Resemblance to charmonium decays.

It was argued [18] that pure glueball decays may bear resemblance to charmonium decays, e.g., to the $\chi_{c0}(0^{++})$ and $\chi_{c2}(2^{++})$ decays. Both $\chi_{c0}$ and $\chi_{c2}$ decays may proceed via two steps: first the $c\bar{c}$ pair annihilate into two gluons, and then the two gluons hadronize into light mesons and baryons. The gluon hadronization appears to be flavor-symmetric. This is supported by the $\chi_{c0}$ and $\chi_{c2}$ decays, e.g., $\chi_{c0}$ is found to have the same decay rate to $\pi^+\pi^-$ as to $K^+K^-$, and the same decay rate to $\pi^+\pi^-\pi^+\pi^-$ as to $\pi^+\pi^-K^+K^-$, and this is also true for $\chi_{c2}$ decays. For a glueball, say, a $2^{++}$ glueball, its decay proceeds via two gluon hadronization, which is similar to the second step of the $\chi_{c2}$ decay. Therefore, a pure $2^{++}$ glueball may have flavor-symmetric decays. Furthermore, the $2^{++}$ glueball, if lying in the 2230 MeV region, can only have little mixing with nearby L=3 $2^{++}$ quarkonium states, because these $q\bar{q}$ states have vanishing wave functions at the origin due to high angular momentum barrier which will prevent the $q\bar{q}$ pair from being annihilated into gluons and then mixed with the $2^{++}$ glueball. This might explain why $\xi(2230)$ has flavor-symmetric couplings to $\pi^+\pi^-$ and $K^+K^-$, if it is nearly a pure $2^{++}$ glueball. In addition, the gluon hadronization leads to many decay modes for $\chi_{c0}$ and $\chi_{c2}$, therefore the $2^{++}$ glueball may also have many decay modes. In comparison, the observed branching ratios for $\xi(2230) \rightarrow \pi^+\pi^-, K^+K^-, K_SK_S, p\bar{p}$ may not exceed 6 percent. This might be very different from the conventional $q\bar{q}$ mesons, which usually have some dominant two-body decay modes.

Above discussions indicate that the decay pattern of glueballs could be rather complicated, and a deeper theoretical understanding is needed to reduce the uncertainties. As for the glueball mass spectrum, despite the remarkable progress made in lattice QCD calculations [35][22][36], uncertainties in estimating glueball masses are still not small. For instance, for $0^{++}$ glueball UKQCD group gives $M = 1550 \pm 50$ MeV [22], while IBM group gets $M = 1740 \pm 71$ MeV and $\Gamma = 108 \pm 29$ MeV [36].

Another progress in the lattice calculation is the glueball matrix elements. For example, a calculation for $<0|Tr(g^2G_{\mu\nu}G_{\mu\nu})|G>$ predicts a branching ratio of $5 \times 10^{-3}$ in $J/\psi$ radiative decays for $0^{++}$ glueball [37]. This may provide useful information on distinguishing between $f_0(1500)$ and $\theta(1720)$, or other possible candidates for $0^{++}$ glueball. If $f_0(1500)$ is the $0^{++}$ glueball, it should have some important decay modes (e.g., $4\pi$) to show up in $J/\psi$ radiative decays.

In summary, while the situation in searching for glueballs via charmonium decays is very encouraging, especially with the $\tau$-charm factory in the future, more theoretical work should be done to make more certain predictions on the glueball mass spectrum, the widths, the transition matrix elements, and in particular the decay patterns.
IV. Prompt Charmonium Production at Tevatron and Fragmentation of Quarks and Gluons

The study of charmonium in high energy hadron collisions may provide an important testing ground for both perturbative QCD and nonperturbative QCD.

In earlier calculations [38], in hadronic collisions the leading order processes
\[ gg \rightarrow g\psi, \quad gg, q\bar{q} \rightarrow g\chi_c(\chi_c \rightarrow \gamma\psi), \quad qg \rightarrow q\chi_c(\chi_c \rightarrow \gamma\psi), \]  
(8)
were assumed to give dominant contributions to the cross section. But they could not reproduce the observed data for charmonium with large transverse momentum. This implies that some new production mechanisms should be important. These are the quark fragmentation and gluon fragmentation.

1. Quark Fragmentation

In essence the quark fragmentation was first numerically evaluated in a calculation for the \( Z^0 \) decay \( Z^0 \rightarrow \psi\bar{c}c \) by Barger, Cheung, and Keung [40] (for other earlier discussions on fragmentation mechanisms see ref. [41]). This decay proceeds via \( Z^0 \rightarrow c\bar{c} \), followed by the splitting \( c \rightarrow \psi c \) or \( \bar{c} \rightarrow \psi \bar{c} \) (see Fig.1), of which the rate is two orders of magnitude larger than that for \( Z^0 \rightarrow \psi gg \) [39], because the fragmentation contribution is enhanced by a factor of \((M_Z/m_c)^2\) due to the fact that in fragmentation the charmonium \((c\bar{c} \text{ bound state})\) is produced with a separation of order \( 1/m_c \) rather than \( 1/m_Z \) as in the previous short-distance processes, e.g., \( Z^0 \rightarrow \psi gg \).

![Fig.1 The quark fragmentation mechanism. \( \psi \) is produced by the charm quark splitting \( c \rightarrow \psi c \).](image)

These numerical calculations, which are based on the fragmentation mechanisms, can be approximately (in the limit \( m_c/m_Z \rightarrow 0 \)) re-expressed in a more clear and concise manner in terms of the quark fragmentation functions, which were studied analytically by Chang and Chen [42] [43], and by Braaten, Cheung, and Yuan [44]. The quark fragmentation functions can be calculated in QCD using the Feynman diagram shown in Fig. 1. For instance, the fragmentation function \( D_{c \rightarrow \psi}(z, \mu) \), which describes the probability of a charm quark to split into the \( J/\psi \) with longitudinal momentum...
fraction $z$ and at scale $\mu$, is given by\cite{14}

$$D_{c\to \psi}(z, 3m_c) = \frac{8}{27\pi} \alpha_s(2m_c)^2 \frac{|R(0)|^2 (1 - z)^2 (16 - 32z + 72z^2 - 32z^3 + 5z^4)}{(2 - z)^6}, \quad (9)$$

where $\mu = 3m_c$ and $R(0)$ is the radial wave function at the origin of $J/\psi$. Large logarithms of $\mu/m_c$ for $\mu = O(m_Z)$ appearing in $D_{i\to \psi}(z, \mu)$ can be summed up by solving the evolution equation

$$\mu \frac{\partial}{\partial \mu} D_{i\to \psi}(z, \mu) = \sum_j \int_z^1 dy \frac{P_{i\to j}(z/y, \mu)}{y} D_{j\to \psi}(y, \mu), \quad (10)$$

where $P_{i\to j}(x, \mu)$ is the Altarelli-Parisi function for the splitting of the parton of type $i$ into a parton of type $j$ with longitudinal momentum fraction $x$. The total rate for inclusive $\psi$ production is approximately

$$\Gamma(Z^0 \to \psi + X) = 2\hat{\Gamma}(Z^0 \to c\bar{c}) \int_0^1 dz D_{c\to \psi}(z, 3m_c). \quad (11)$$

Then the branching ratio for the decay of $Z^0$ into $\psi$ relative to decay into $c\bar{c}$ is

$$\frac{\Gamma(Z^0 \to \psi c\bar{c})}{\Gamma(Z^0 \to c\bar{c})} = 0.0234\alpha_s(2m_c)^2 \frac{|R(0)|^2}{m_c^3} \approx 2 \times 10^{-4}, \quad (12)$$

which agrees with the complete leading order calculation of $Z^0 \to \psi c\bar{c}$ in Ref.\cite{10}.

Using the fragmentation functions, the production rates of the $B_c$ meson are predicted in Ref.\cite{12}. E.g., the branching ratio of $B_c$ in $Z^0$ decay is about $R \approx 7.2 \times 10^{-5}$ (see also Ref.\cite{13}).

The quark fragmentation functions to P-wave mesons have also been calculated \cite{13} \cite{10}.

2. Gluon Fragmentation

As the quark fragmentation, the gluon fragmentation may also be the dominant production mechanism for heavy quark-antiquark bound states (e.g., charmonium) with large transverse momentum.

In previous calculations, e.g. in the gluon fusion process, charmonium states with large $P_T$ were assumed to be produced by short distance mechanisms, i.e., the $c$ and $\bar{c}$ are created with transverse separations of order $1/P_T$, as shown in Fig.2(a) for $gg \to \eta_c g$. However, in the gluon fragmentation mechanism the $\eta_c$ is produced by the gluon splitting $g \to \eta_c g$ (while $J/\psi$ is produced by $g \to \psi gg$), as shown in Fig.2(b).

For gluon fragmentation, in the kinematic region where the virtual gluon and $\eta_c$ are colinear, the propagator of this gluon is off shell only by an amount of order $m_c$, and enhances the cross section by a factor of $P_T^2/m_c^2$. If $P_T$ is large enough, this will
overcome the extra power of the coupling constant $\alpha_s$, as compared with the short distance leading order process $gg \rightarrow \eta_c g$. The gluon fragmentation functions were calculated by Braaten and Yuan\cite{47}:

$$\int_0^1 dz D_{g \rightarrow \eta_c}(z, 2m_c) = \frac{1}{72\pi} \alpha_s(2m_c)^2 \frac{|R(0)|^2}{m_c^3},$$

(13)

$$\int_0^1 dz D_{g \rightarrow \psi}(z, 2m_c) = (1.2 \times 10^{-3}) \alpha_s(2m_c)^3 \frac{|R(0)|^2}{m_c^3},$$

(14)

where the latter is estimated to be smaller than the former by almost an order of magnitude.

The gluon fragmentation into P-wave heavy quarkonium was also studied\cite{48}. The P-wave state (e.g., $\chi_{cJ}$) can arise from two sources i.e., the production of a color-singlet P-wave state, and the production of a $c\bar{c}$ pair in a color-octet S-wave state, which is then projected onto the $\chi_{cJ}$ wave functions. With two parameters which characterize the long-distance effects, i.e., the derivative of P-wave wavefunction at the origin and the probability for an S-wave color-octet $c\bar{c}$ pair in the color-singlet $\chi_{cJ}$ bound state, the fragmentation probabilities for a high transverse momentum gluon to split into $\chi_{c0}$, $\chi_{c1}$, $\chi_{c2}$ are estimated to be $0.4 \times 10^{-4}$, $1.8 \times 10^{-4}$, $2.4 \times 10^{-4}$, respectively\cite{48}. They could be the main source of $\chi_{cJ}$ production at large $P_T$ in $p\bar{p}$ colliders.

Since fragmentating gluons are approximately transverse, their products are significantly polarized. Cho, Wise, and Trivedi\cite{50} find that in gluon fragmentation to $\chi_{cJ}(1P)$ followed by $\chi_{cJ} \rightarrow \gamma J/\psi$ the helicity levels of $\chi_{c1}$, $\chi_{c2}$, and $J/\psi$ are populated according to certain ratios, e.g., $D_{\chi_{c1}}^{h=0} : D_{\chi_{c1}}^{|h|=1} \approx 1 : 1$, $D_{J/\psi}^{h=0} : D_{J/\psi}^{|h|=1} \approx 1 : 3.4$.

The gluon fragmentation to $J^{PC} = 2^{-+} \ 1D_2$ quarkonia was also studied, and these D-wave state’s polarized fragmentation functions were computed \cite{19}. 

Fig.2(a) A Feynman diagram for $gg \rightarrow c\bar{c}g$ that contributes to $\eta_c$ production at order $\alpha_s^2$; Fig.2(b) A Feynman diagram for $gg \rightarrow c\bar{c}gg$ that contributes to $\eta_c$ production at order $\alpha_s^4$. For the virtual gluon at large $P_T$, with $q_0 = O(P_T)$, $q^2 = O(m_c^2)$, the contribution is dominant.
3. The ψ' surplus problem at the Tevatron

In 1994, theoretical calculations were compared with data on inclusive \( J/\psi \) and \( \psi' \) production at large transverse momentum at the Tevatron \[1\], where large production cross sections were observed. The calculations include both the conventional leading order mechanisms and the charm and gluon fragmentation contributions \[52, 53\].

For \( \psi \) production both fragmentation directly into \( \psi \) and fragmentation into \( \chi_c \) followed by the radiative decay \( \chi_c \rightarrow \psi + \gamma \) are considered. Fragmentation functions for \( g \rightarrow \psi, \ c \rightarrow \psi, \ g \rightarrow \chi_c, \ c \rightarrow \chi_c, \) and \( \gamma \rightarrow \psi \) are used.

These calculations indicate that

1. Fragmentation dominates over the leading-order mechanisms for \( P_T > 5 \) GeV.
2. The dominant production mechanism by an order of magnitude is gluon fragmentation into \( \chi_c \) followed by \( \chi_c \rightarrow \gamma \psi \).

For \( \psi' \) production the fragmentaions \( g \rightarrow \psi', \ c \rightarrow \psi', \ \gamma \rightarrow \psi' \) and the leading order mechanisms are included but no contribution from any higher charmonium states is taken into consideration. The dominant production mechanisms are gluon-gluon fusion for \( P_T < 5 \) GeV, and charm quark fragmentation into \( \psi' \) for large \( P_T \).

However, the calculated production cross section of \( \psi' \) is too small by more than an order of magnitude (roughly a factor of 30) \[53, 54\]. This serious disagreement, the so-called \( \psi' \) surplus problem, has caused many theoretical speculations.

The radically excited \( 2^3P_{1,2} \) (\( \chi_{c1}(2P) \) and \( \chi_{c2}(2P) \)) states have been suggested to explain the \( \psi' \) surplus problem \[50, 50, 55\]. These states can be produced via gluon and charm fragmentation as well as the conventional gluon fusion mechanism, and then decay into \( \gamma \psi' \) through E1 transitions. Large branching ratios of \( B(\chi_{c1}(2P) \rightarrow \psi'(2S) + \gamma) = (5 \sim 10)\% \) (J=1, 2) are required to explain the \( \psi' \) production enhancement. Within the potential model with linear confinement, the masses of these 2P states are predicted to be, e.g., \( M(\chi_{c0}(2P)) = 3920 \) MeV, \( M(\chi_{c1}(2P)) = 3950 \) MeV, and \( M(\chi_{c2}(2P)) = 3980 \) MeV \[57\], therefore OZI-allowed hadronic decays like \( \chi_{c0}(2P) \rightarrow D\bar{D}, \ \chi_{c1}(2P) \rightarrow D^*\bar{D} + c.c., \) and \( \chi_{c2}(2P) \rightarrow D\bar{D}, \ D^*\bar{D} + c.c., \) can occur. It is not clear whether these hadronic widths are narrow, making the branching ratios \( B(\chi_{c1}(2P) \rightarrow \psi'(2S) + \gamma) \) large enough to explain the \( \psi' \) production data.

One possibility is that since decays \( \chi_{c1}(2P) \rightarrow D\bar{D}, \ D^*\bar{D} + c.c. \) proceed via \( L = 2 \) partial waves, they could be suppressed \[50\]. These OZI-allowed hadronic decays are estimated in a flux-tube model and they could be further suppressed (aside from the D-wave phase space for \( \chi_{c2}(2P) \)) due to the node structure in the radial wave functions of excited states \[58\]. With suitable parameters used, the widths of \( \chi_{c1}(2P) \) and \( \chi_{c2}(2P) \) could be as narrow as \( \Gamma \approx (1 \sim 10) \) MeV.

There is another possibility that the \( \chi_{c1}(2P) \) could lie bellow the \( D^*\bar{D} \) threshold, and then with roughly estimated \( \Gamma(\chi_{c1}(2P) \rightarrow \text{light hadrons}) \approx 640 \) KeV, \( \Gamma(\chi_{c1}(2P) \rightarrow \gamma \psi') \approx 85 \) KeV, one could get \( B(\chi_{c1}(2P) \rightarrow \gamma \psi') \approx 12\% \) \[53\]. This possibility relies on the expectation that color screening effect of light quark pair on the heavy \( Q\bar{Q} \) potential, observed in lattice QCD calculations, would lead to a screened confinement.
potential which makes the level spacings of excited $c\bar{c}$ states lower than that obtained using the linear potential (e.g., $\psi(4160)$ and $\psi(4415)$ could be 4S and 5S rather than 2D and 4S states, respectively).

Moreover, it is suggested that the $c\bar{c}g$ hybrid states could make a significant contribution to $J/\psi$ and $\psi'$ signals at the Tevatron$^{55}$, since the color octet production mechanism is expected to be important, and hybrid states contain gluonic excitations in which the $c\bar{c}$ are in the S-wave color octet configuration. In particular, the negative parity hybrid states, including $(0^+, 1^-, 2^-)$, lying in the range $4.2 \pm 0.2$GeV, could be a copious source of $J/\psi$ and $\psi'$, through radiative and hadronic transitions.

4. Color Octet Fragmentation Mechanism

Based on a general factorization analysis of the annihilation and production of heavy quarkonium $^{50, 51}$. Braaten and Fleming proposed a new mechanism, i.e. the color-octet fragmentation for the $J/\psi$ and $\psi'$ production at large $P_T$ $^{52}$.

In the framework of NRQCD theory $^{61}$, which is based on a double power series expansion in the strong coupling constant $\alpha_s$ and the small velocity parameter $v$ of heavy quark, the fragmentation functions can be factored into short-distance coefficients and long-distance factors that contain all the nonperturbative dynamics of the formation of a bound state containing the $c\bar{c}$ pair. E.g., for $g \rightarrow \psi$ fragmentation

$$D_{g\rightarrow\psi}(z, \mu) = \sum_n d_n(z, \mu) < 0|O_n^\psi|0 >,$$

(15)

where $O_n^\psi$ are local four fermion (quark) operators.

For the physical $\psi$ state, the wavefunction can be expressed as Fork state decompositions which include dynamical gluons and color-octet $(Q\bar{Q})_8$ components

$$|\psi > = O(1)|(Q\bar{Q})_1(3S_1) > + O(v)|(Q\bar{Q})_8(3P_1)g >$$

$$+ O(v^2)|(Q\bar{Q})_8(3S_1)gg > + \cdots.$$  

(16)

Therefore there are two mechanisms for gluon fragmentation into $\psi$:

(1)Color-singlet fragmentation $g^* \rightarrow c\bar{c}gg$. Here $c\bar{c}$ is produced in a color-singlet $3S_1$ state. The matrix element $< O_1^\psi(3S_1) >$ is of order $m^3 c v^3$, which is related to the Fork state $|(c\bar{c})_1(3S_1) >$ in $\psi$, so the contribution to fragmentation function is of order $\alpha^3 c v^3$.

(2)Color-octet fragmentation $g^* \rightarrow c\bar{c}$. Here $c\bar{c}$ is produced in a color-octet $3S_1$ state. The matrix element $< O_8^\psi(3S_1) >$ is of order $m^3 c v^7$, which is related to the Fork state $|(c\bar{c})_8(3S_1)gg >$ in $\psi$, so the contribution to fragmentation function is of order $\alpha c v^7$.

It is clear that the color-octet fragmentation $g^* \rightarrow c\bar{c}$ is enhanced by a factor of $\sim \alpha_s^{-2}$ from the short-distance coefficients, and suppressed by a factor of $\sim v^4$ from the long-distance matrix elements, as compared with the color-singlet fragmentation.
Since for charmonium $v^2 \approx 0.25 \sim 0.30$ is not very small, the color-octet fragmentation could be dominant in some cases, e.g., in the $\psi'$ production at large transverse momentum.

In the case of $\psi'$, if the observed large cross section is really due to color-octet fragmentation the matrix element $\langle O_{\psi'}^{(3S_1)} \rangle$ will be determined by fitting the CDF data on the $\psi'$ production rate at large $P_T$

$$\langle O_{\psi'}^{(3S_1)} \rangle = 0.0042 GeV^3,$$  \hspace{1cm} (17)

while the color-singlet matrix element $\langle O_{\psi}^{(3S_1)} \rangle$ is determined by the $\psi'$ leptonic decay width which is related to the wave function at the origin

$$\langle O_{\psi}^{(3S_1)} \rangle \approx \frac{3}{2\pi}|R_\psi|^2 = 0.11 GeV^3.$$ \hspace{1cm} (18)

The color-octet matrix element is smaller by a factor of 25 than the color-singlet matrix element, consistent with suppression by $v^4$. Therefore the color-octet fragmentation could be a possible solution to the $\psi'$ surplus problem.

The color-octet fragmentation will also make a substantial contribution to the $J/\psi$ production at large $P_T$, and may compete with gluon fragmentation into $\chi_{cJ}$ followed by $\chi_{cJ} \rightarrow \gamma J/\psi$.

The color-octet fragmentation mechanism might be supported by the new data from CDF\cite{51} and D0\cite{64} at the Tevatron. New results for the fraction of $J/\psi$ which come from the radiative decay of $\chi_c$ are (see Fig.3 for the CDF result)

$$CDF: \quad f_{\chi}^{J/\psi} = (32.3 \pm 2.0 \pm 8.5)\% \quad (P_T^{J/\psi} > 4 GeV, |\eta^{J/\psi}| < 0.6), \quad (19)$$

$$D0: \quad f_{\chi}^{J/\psi} = (30 \pm 7 \pm 10)\% \quad (P_T^{J/\psi} > 8 GeV, |\eta^{J/\psi}| < 0.6). \quad (20)$$

Fig.3 The fraction of $J/\psi$ from $\chi_c$ as a function of $P_T^{J/\psi}$ with the contribution from $b$ quark’s removed, measured by CDF \cite{51}. 

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This implies that the majority of prompt $J/\psi$ at large $P_T$ do not come from $\chi_c$, and the gluon fragmentation into $\chi_c$ is not the dominant mechanism for $J/\psi$ production at large $P_T$. The observed production cross section of $J/\psi$ from $\chi_c$ is in reasonable agreement with the theoretical calculations while the direct $J/\psi$ production cross section is a large factor above the prediction (see Fig.4 for the CDF result).

Although this result might favor the color-octet fragmentation mechanism for the direct production of $J/\psi$, it is still premature to claim that it is the real source of $J/\psi$ production.

In order to further test the color-octet fragmentation mechanism for the production of $J/\psi$ and, in particular, $\psi'$ at the Tevatron, some studies are required. First, the produced $\psi'$ should be transversely polarized [49], and the experimental observation of a large transverse $\psi'$ spin alignment would provide strong support for the color-octet production mechanism of $\psi'$. Another important test is to apply the same mechanism to the $b\bar{b}$ systems. The integrated and differential production cross sections for the $\Upsilon(1S), \Upsilon(2S), \Upsilon(3S)$ have been measured by both CDF [65] and D0 [64].

![Fig.4 Differential cross sections of prompt $J/\psi$ as a function of $P_{TJ/\psi}$ with the contribution from $b$ quark’s removed, measured by CDF [53]. The dotted curve represents the total fragmentation contribution (but without the color-octet fragmentation), and the dashed curve represents the leading-order contribution [53].](image-url)
The production rates are generally found to be higher than that with color-singlet fragmentations. The color-octet production mechanism does help to explain some of the discrepancies [66].

In this connection it is worthwhile to note that the problem of $J/\psi$ and especially $\psi'$ surplus production has also been observed by the fixed target experiment (e.g., in 800 GeV proton-gold collisions) [67]. In collisions at lower energies, fragmentation is not expected to be dominant. It is not clear whether the $\psi'$ surplus observed both at the Tevatron and fixed-target (with the same enhancement factor of about 25 relative to the expected production rates) has the same origin or not. Further experimental and theoretical investigations are needed.

V. Some Results in Charmonium and Open Charm Physics

Here some theoretical results on charmonium and open-charm hadrons are reported.

- The $Q\bar{Q}$ spin dependent potential.

There have been many discussions about the $Q\bar{Q}$ spin dependent potential (see e.g. [68] [69] [70]). A new formula for the heavy-quark-antiquark spin-dependent potential is given using the techniques developed in heavy-quark effective theory [71]. The leading logarithmic quark mass terms emerging from the loop contributions are explicitly extracted and summed up. There is no renormalization scale ambiguity in this new formula. The spin-dependent potential in the new formula is expressed in terms of three independent color-electric and color-magnetic field correlation functions, and it includes both the Eichten-Feinberg formula [68] [69] and one-loop QCD result [70] as special cases. For hyperfine splittings with $\Lambda_{\overline{MS}} = 200 - 500 MeV$, the new formula gives [72]

$$M(J/\psi) - M(\eta_c) \approx 110 - 120 MeV, \quad M(\Upsilon) - M(\eta_b) \approx 45 - 50 MeV,$$

and

$$M(1P_1) - M(3P_J) \approx 2 - 4 MeV$$

for $c\bar{c}$, which is larger than the present E760 result ($\sim 0.9 MeV$) [73], and other theoretical predictions (e.g. [74]). But this tiny mass difference may be sensitive to other effects, e.g., the coupled-channel mass shifts.

A set of general relations between the spin-independent and spin-dependent potentials of heavy quark and antiquark interactions are derived from reparameterization invariance in the Heavy Quark Effective Theory [75]. They are useful in understanding the spin-independent and spin-dependent relativistic corrections to the leading order nonrelativistic potential.

- Relativistic corrections to $Q\bar{Q}$ decay widths and the determination of $\alpha_s(m_Q)$.

Charmonium mass spectrum and decay rates can be very useful in determining the QCD coupling constant $\alpha_s$. In recent years remarkable progresses have been made in lattice calculations [76] [77]. On the other hand, many decay processes may be subject to substantial relativistic corrections, making the determination of $\alpha_s$ quite uncertain [78] [79].
The decay rates of $V \to 3g$ and $V \to e^+e^-$ for $V = J/\psi$ and $\Upsilon$ may be expressed in terms of the Bethe-Salpeter amplitudes, and to the first order relativistic correction and QCD radiative correction it is found that \cite{80}
\[
\Gamma(V \to e^+e^-) = \frac{4\pi\alpha^2\epsilon^2}{m_Q^2} \int d^3q (1 - \frac{2q^2}{3m_Q^2}) |\psi_{Sch}(\vec{q})|^2 (1 - \frac{16\alpha_s}{3\pi}),
\]
\[
\Gamma(V \to 3g) = \frac{40(\pi^2 - 9)\alpha_s^3(m_Q)}{81m_Q^2} \int d^3q (1 - 2.95 \frac{q^2}{m_Q^2}) |\psi_{Sch}(\vec{q})|^2 (1 - \frac{S_Q\alpha_s}{\pi}), \quad (22)
\]
where $S_c = 3.7$, $S_b = 4.9$ (defined in the $\overline{MS}$ scheme at the heavy quark mass scale) \cite{78,79}. This result shows explicitly that the relativistic correction suppresses the gluonic decay much more severely than the leptonic decay. Using the meson wavefunctions obtained by solving the BS equation with a QCD-inspired interquark potential, and the experimental values of decay rates \cite{81}, it is found that \cite{80}
\[
\alpha_s(m_c) = 0.26 - 0.29, \quad \alpha_s(m_b) = 0.19 - 0.21, \quad (23)
\]
at $m_c = 1.5 \text{ GeV}$ and $m_b = 4.9 \text{ GeV}$. These values for the QCD coupling constant are substantially enhanced, as compared with the ones obtained without relativistic corrections. However, it should be emphasized that these numerical results can only serve as an improved estimate rather than a precise determination, due to large theoretical uncertainties related to the scheme dependence of QCD radiative corrections \cite{82} and higher order relativistic corrections. This result is consistent with that obtained using finite size vertex corrections \cite{83}.

- Heavy meson decay constants.

Discussions on the heavy meson decay constants are very extensive. In the framework of heavy quark effective theory (HQET), QCD sum rules are used to estimate the nonperturbative effects \cite{84,85,86,87}. The first systematic investigation was given in \cite{84}, and a further improvement was obtained by separating the subleading order from the leading one \cite{86}.

In a recent work \cite{88} the SU(3) breaking effects in the leading and subleading parameters appeared in the heavy quark expansion of decay constants of the heavy-light mesons are systematically analyzed to two loops accuracy using QCD sum rules. It is found that the SU(3) breaking effects in the decay constant of the pseudoscalar are respectively
\[
f_{B_s}/f_B = 1.17 \pm 0.03, \quad f_{D_s}/f_D = 1.13 \pm 0.03. \quad (24)
\]
These results are in agreement with recent lattice QCD calculations \cite{77}. In addition, the ratios of vector to pseudoscalar meson decay constants are found to be
\[
f_{B_s}/f_{B_s} = f_{B_s}/f_B = 1.05 \pm 0.02, \quad (25)
\]
and the SU(3) breaking effect in the mass is about $82 \pm 8\text{MeV}$. 

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Another approach to estimating nonperturbative effects on heavy mesons is to combine HQET with chiral perturbation theory [89]. In the framework of the heavy-light chiral perturbation theory (HLCPT) the heavy meson decay constants are discussed [90] and the effects of excited states on the chiral loop corrections are further considered [91].

In a recent work the vector meson contributions are introduced in HLCPT and the lagrangian and current to the order $1/m_Q^2$ are constructed [92]. With this, to the order $1/\Lambda_{csb}^2$ ($\Lambda_{csb}$ is the chiral symmetry breaking scale), corrections to $f_D$ and $f_B$ arising from coupled-channel effects to order $1/m_c$ and $1/m_b$ are calculated. At the tree level in HLCPT, using the relativistic B-S equation with kernel containing a confinement term and a gluon exchange term in a covariant generalization of the Coulomb gauge [93], the decay constants $f_D^{(0)}$ and $f_B^{(0)}$ when $m_Q \to \infty$ as well as the $1/m_Q$ corrections are calculated. HLCPT and the heavy quark effective theory (HQET) are matched at the scale $\Lambda_{csb}$. Adding the perturbative and nonperturbative contributions the values for $f_D$ and $f_B$ are found to be

$$f_D \approx f_B \approx 200 \text{ MeV},$$

which is in agreement with lattice calculations [77].

We now turn to some new experimental results in open charm physics. The CLEO Collaboration has given following results.

- More accurate or the first measurements of $D^0$ decays [94].

| Channel       | B(%)            | PDG(%)          |
|---------------|-----------------|-----------------|
| $K^+K^-$      | 0.455±0.029±0.032 | 0.454±0.029     |
| $K^0\bar{K}^0$ | 0.048±0.012±0.013 | 0.11±0.04       |
| $K_S^0\bar{K}_S^0K_S^0\bar{K}_S^0$ | 0.074±0.010±0.018 | 0.089±0.025    |
| $K_S^0\bar{K}_S^0\pi^0$ | <0.063 at 90 CL%    |                 |
| $K^+K^-\pi^0$ | 0.107±0.030      |                 |

The theoretical prediction for $B(K^+K^-)$ is in the range 0.14-0.6, and for $B(K^0\bar{K}^0)$ is 0-0.3.

- Observation of the Cabibbo suppressed charmed baryon decay of $\Lambda_c^+ \to p\phi$ and $pK^+K^-$, compared with $\Lambda_c^- \to pK^-\pi^+$ [95].

$$B(p\phi)/B(pK\pi) = 0.024 \pm 0.006 \pm 0.003,$$

$$B(pKK)/B(pK\pi) = 0.039 \pm 0.009 \pm 0.007,$$

$$B(p\phi)/B(pKK) = 0.62 \pm 0.20 \pm 0.12.$$

The theoretical predictions range from 0.01 to 0.05 for $B(p\phi)/B(pK\pi)$.

- Measurement of the isospin-violating decay $D_s^{*+} \to D_s^+\pi^0$ [96].

$$\frac{\Gamma(D_s^{*+} \to D_s^+\pi^0)}{\Gamma(D_s^{*+} \to D_s^+\gamma)} = 0.062^{+0.020}_{-0.018} \pm 0.022.$$
This isospin-violating decay is expected to proceed through OZI-allowed decay $D_s^{+} \rightarrow D_s^{+} \eta$ (via the $s\bar{s}$ component in $\eta$) and the $\eta - \pi^0$ mixing [97]. This decay also implies that $D_s^{+}$ has natural spin-parity (most likely $1^-$).

- Measurement of the relative branching ratios of $D_s^+$ to $\eta e^+\nu$ and $\eta' e^+\nu$, compared to $\phi e^+\nu$ [98].

$$\frac{B(D_s^+ \rightarrow \eta e^+\nu)}{B(D_s^+ \rightarrow \phi e^+\nu)} = 1.24 \pm 0.12 \pm 0.15. \quad (31)$$

$$\frac{B(D_s^+ \rightarrow \eta' e^+\nu)}{B(D_s^+ \rightarrow \phi e^+\nu)} = 0.43 \pm 0.11 \pm 0.07. \quad (32)$$

These results favor the prediction of the ISGW2 model [99].

- Measurement of $\Xi_c^+$ decay branching ratios relative to $\Xi_c^+ \rightarrow \Xi^- \pi^+ \pi^+$ [100].

| Decay Mode      | events | $B/B(\Xi_c^+ \rightarrow \Xi^- \pi^+ \pi^+)$ |
|-----------------|--------|---------------------------------------------|
| $\Sigma^+ K^- \pi^+$ | 119±23 | 1.18±0.26±0.17                             |
| $\Sigma^+ K^+\pi^0$    | 61±17  | 0.92±0.27±0.14                             |
| $\Lambda K^- \pi^+ \pi^+$ | 61±15  | 0.58±0.16±0.07                             |
| $\Theta^- \pi^+ \pi^+$  | 131±14 | 1.0                                         |

There are also some experimental results from the ARGUS Collaboration.

- Leptonic branching ratios of $D^0$ [101].

$$B(D^0 \rightarrow e^+\nu e X) = 6.9 \pm 0.3 \pm 0.5\%, \quad (33)$$

$$B(D^0 \rightarrow \mu^+\nu_{\mu} X) = 6.0 \pm 0.7 \pm 1.2\%. \quad (34)$$

These values are smaller than the world average values [81].

- Measurement of the decay $D_s^+(2573) \rightarrow D^0 K^+$ [102]. The observed mass and width $\Gamma = (10.4\pm8.3\pm3.0) \text{ MeV}$ of this resonance are consistent with that obtained by CLEO.

- Evidence for the $\Lambda_c^{*+}(2593)$ production [103].

Finally, BES Collaboration has reported the leptonic branching ratio of $D_s$ using $(148 \pm 18 \pm 13) D_s$ events [104].

$$B(D_s^+ \rightarrow e^+\nu e X) = (10.0^{+6.5+1.3}_{-4.6-1.2})\%. \quad (35)$$

VI. Conclusions

While impressive progress in experiment has been made in physics in the charm energy region, some theoretical issues need to be clarified.

The new data and puzzles in exclusive hadronic decays of $J/\psi$ and $\psi'$ give new challenges to the theory of hadronic decays.
With the new observation for $\xi(2230)$ and $f_0(1500)$, the situation in searching for glueballs is encouraging, but theoretical uncertainties related to the properties of glueballs still remain and need to be further reduced.

For the prompt production of charmonium at large transverse momentum, gluon and quark fragmentations dominate over leading-order parton fusions. Color-singlet fragmentation is not the dominant mechanism for $J/\psi$ and $\psi'$ production. Color-octet fragmentation seems to be important to explain the $J/\psi$ and, in particular, the $\psi'$ excess, but further tests are required. The mechanism of charmonium production at fixed-target also needs studying.

The study of open charm physics is in continuous progress. This is important for testing the Standard Model and understanding both perturbative and nonperturbative QCD.

In the future, with new experiments at $e^+e^-$ colliders, hadronic colliders, fixed target, and, in particular, at the proposed $\tau$-charm factory, and with the theoretical progress in lattice QCD and other nonperturbative methods, a deeper understanding of physics in the charm energy region will be achieved.

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