Spectroscopy of Mesons with Heavy Quarks

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Abstract

I will give a concise overview of mesons with heavy quarks including p-wave charmed mesons and charmonium (or charmonium-like) states such as X(3872), Y(4260), X(3940), Y(3940), Z(3930) etc. The effect from the nearby S-wave open channels on the quark model spectrum is emphasized.

Key words: Charmed mesons, charmonium, coupled-channel effect

PACS: 14.40.Lb, 14.40.Gx

1. QCD and hadron physics

QCD is the underlying theory of strong interaction, which has three fundamental properties: asymptotic freedom, confinement, and approximate chiral symmetry and its spontaneous breaking. Perturbative QCD has been tested to very high accuracy. But the low energy sector of QCD (i.e., hadron physics) still remains very challenging. Precision-test of Standard Model and search for new physics require good knowledge of hadrons as inputs such as parton distribution functions, hadron distribution amplitudes etc.

The motion and interaction of hadrons differ from those of nuclei and elementary particles like quarks, gluons, leptons and gauge bosons. Hadron physics is the bridge between nuclear physics and particle physics. The famous Higgs mechanism contributes around 20 MeV to the nucleon mass through current quark mass. Nearly all the mass of the visible matter in our universe comes from the non-perturbative QCD interaction. Therefore study of hadron spectroscopy explores the mechanism of confinement and chiral symmetry breaking, and the mass origin.

Quark model is quite successful in the classification of hadrons although it’s not derived from QCD. Any state with quark content other than $q\bar{q}$ or $qqq$ is beyond the naive quark
model. But quark model can’t be the whole story. QCD may allow much richer hadron spectrum such as glueballs, hybrid mesons/baryons, multiquark states, hadron molecules. Although experimental search of these non-conventional states started many years ago, none of them has been established without controversy experimentally!

Typical signatures of these non-conventional states include:
- Exotic flavor quantum number like $\theta^+$
- Exotic $J^{PC}$ quantum number like $1^{-+}$ exotic meson
- Overpopulation of the QM spectrum like the scalar isoscalar spectrum below 1.9 GeV: $\sigma$, $f_0(980)$, $f_0(1370)$, $f_0(1500)$, $f_0(1710)$, $f_0(1790)$, $f_0(1810)$.

In this talk I will review the recent progress on the P-wave charmed mesons in the past several years, especially $D_s^0(2308/2407)$, $D_s^0(2427)$, $D_{s1}^0(2317)$, $D_{s1}^* (2460)$. I will also discuss the important progress on the charmonium and charmonium-like system including $X(3872)$, $X(3940)$, $Y(3940)$, $Y(4260)$, $Z(3930)$ etc. Interested readers may consult the recent review on new hadron states [1].

2. Charmed mesons

Heavy quark expansion provides a systematic method to deal with hadrons with a single heavy quark. The angular momentum $j_I$ of the light quark in the $Q\bar{q}$ system is a good quantum number in the heavy quark limit. Heavy mesons form doublets with different $j_I$ and parity. For $L = 0$, we have the ground doublet $(0^-, 1^-)$. For the $L = 1$ P-wave states, we have two doublets: $(0^+, 1^+)$, $(1^+, 2^+)$, $(1^-, 1^-)$, and $(1^+, 2^+)$ doublets.

For the non-strange $(0^+, 1^+)$ doublet decay through s-wave. They are very broad with a width around 20 MeV. They form narrow with a width around 20 MeV. There was one measurement of the $1^+$ mass from Belle Collaboration $m_{D_1^+} = 2427 \pm 26 \pm 25$ MeV with a large width $384^{+107}_{-75} \pm 74$ MeV [2], where we use the star to indicate this $1^+$ state belongs to the $(0^+, 1^+)$ doublet. For the $0^+$ state, there were two measurements. FOCUS Collaborations reported $m_{D_0^*} = 2308 \pm 17 \pm 32$ MeV with a width $276 \pm 21 \pm 63$ MeV [3] while BELLE observed it at $2407 \pm 21 \pm 35$ MeV with a width $240 \pm 55 \pm 59$ MeV [2].

For the strange doublet, we have $m_{D_{s0}^*} = 2317$ MeV, $m_{D_{s}^*} = 2459$ MeV [4]. $D_{s0}^*$ and $D_{s1}^*$ lie below DK (D*K) threshold. They are roughly 160 MeV below quark model prediction [5]. Both of them are extremely narrow. Their strong decays violate isospin symmetry and occur with help of a virtual $\eta$ meson: $D_{s0}^* \to D_s \eta \to D_s \pi^0$. The mass of $D_{s0}^*$ from three lattice QCD simulations is still larger than experimental value [6,7,8]. Naively one would expect that $D_{s0}^*(2317)$ lies 100 MeV above $D_0^*(2108/2407)$ because of the mass difference between strange and up quarks. Now arise the two puzzles: (1) why is the mass of $D_{s0}^*(2317)$ so low? (2) why are $D_0$ and $D_0^*$ nearly degenerate?

The low mass of $D_{s0}^*(2317)$ inspired various tetraquark schemes. For example, if $D_0^*$ and $D_{s0}^*$ were in the anti-symmetric 3 multiplet, their flavor wave functions are [9]

$$|D_0^*\rangle = \frac{1}{2}(e(s(u\bar{u}-s\bar{u})-d(d\bar{u}-u\bar{d}))) \ .$$

$$|D_{s0}^*\rangle = \frac{1}{2}(e(u(u\bar{u}-s\bar{u})-d(d\bar{s}-s\bar{d}))) \ .$$

(1)

(2)
Since they contain the same amount of strange, they would have roughly the same mass. But tetraquarks always contain the color-singlet times color-singlet component in their color wave function. They would fall apart easily and become very broad. There always exist two difficult issues for the tetraquark interpretation: (1) where are the conventional \((0^+, 1^+)\) states in the quark model? (2) where are those partner states in the same tetraquark multiplet? In fact, Babar collaboration scanned around 2.31 GeV, 2.46 GeV and below 2.7 GeV. Not surprisingly, they found neither additional \((0^+, 1^+)\) states nor their spin-flavor partner states.

Belle, Babar and Cleo collaborations measured the ratio of radiative and strong decay widths of \(D^*_s(2317)\) and \(D^*_s(2460)\), which is collected in Table 1. Assuming \(D^*_s(2317)\) and \(D^*_s(2460)\) are conventional \(c\bar{s}\) mesons, theoretical ratio from light-cone QCD sum rules \([13,14]\) and \(3P_0\) model \([15]\) is consistent with Belle/Babar’s recent data. Coupled channel effects may be the origin of the low mass puzzle of \(D^*_s(2317)\) and \(D^*_s(2460)\) since they have the same quantum number as S-wave \(DK(D^*K)\) continuum and lie very close to \(DK(D^*K)\) threshold (within 46 MeV). Moreover the \(D^*_s(2317)DK\) coupling is very large. Within the quark model, the configuration mixing effects between the "bare" \((0^+, 1^+)\) and \(DK(D^*K)\) may lower the mass of \(D^*_s(2317)\) and \(D^*_s(2460)\). Within the QCD sum rule framework, the DK continuum contribution may be important \([16]\). This mechanism also provides a possible explanation why quenched lattice QCD simulations get a higher mass since quenched approximation ignores the meson loop.

### 3. Charmonium or charmonium-like states

The charmonium system is the playground of new phenomenological models of the low-energy strong interaction since QCD can not be solved analytically at present. The potential model is widely used. Usually there are three pieces in the potential. The first one is a central potential from one gluon exchange and the linear confinement. The second term is the spin-spin interaction which splits the spin singlet and triplet states like \(J/\psi\) and \(\eta_c\). The third piece is the spin-orbit interaction which is responsible for the splitting among states like \(\chi_{c0,1,2}\).

There has been important progress in the charmonium spectroscopy in the past few years. Several previously "missing" states were observed, which are expected in the quark model. Quite a few unexpected states are discovered experimentally, seriously challenging the quark model. These new states were named alphabetically as XYZ etc.
Aspects of these XYZ states have been reviewed in literature, for example in Refs. [17,18,19,20,21,22].

3.1. Z(3930)

Belle collaboration observed Z(3930) in the $D\bar{D}$ channel in the electron positron annihilation [23]. Since this state was produced through the two photon reaction, its parity and C-parity are even. From angular distribution of final states, its angular momentum was found to be two. Its total width is around 20 MeV. The property of this tensor state matches well with $\chi'_c$ in the quark model, although its expected $D^*\bar{D}$ mode has not been discovered yet.

It’s interesting to compare Z(3930) with quark model prediction of the mass of $\chi'_c$, which ranges from 3972 MeV to 4030 MeV. In other words, quark model predictions of the $\chi'_c$ mass is always 40-100 MeV higher. I want to emphasize that this may be the typical accuracy of quark model for the higher charmonium states above open charm decay threshold.

3.2. X(3940)

In the recoil mass spectrum of $J/\psi$ in the electron positron annihilation, Belle observed X(3940) in the $D\bar{D}^*$ channel but not in the $DD$ and $\omega J/\psi$ modes [24]. Its C-parity is even with a width less than 52 MeV. Such a decay pattern is typical of $\chi'_{c1}$.

But the ground state $\chi_{c1}$ is not seen in the same experiment. Hence X(3940) does not look like $\chi'_{c1}$. Instead X(3940) may be $\eta''_c$ except that it’s 100 MeV below the QM prediction.

3.3. Y(3940)

Belle collaboration observed a broad threshold enhancement Y(3940) in $\omega J/\psi$ channel in the $B \rightarrow K\omega J/\psi$ decay [25]. If this enhancement is taken as a particle, its width is around 92 MeV. The hidden charm decay mode $Y(3940) \rightarrow \omega J/\psi$ violates $SU_F(3)$ flavor symmetry. It’s very unusual its width is larger than 7 MeV! Such a decay pattern is very puzzling while its dominant decay mode remains to be discovered. This state has not been confirmed by other collaborations yet.

3.4. X(3872)

3.4.1. Experimental information and its quantum number

Belle collaboration first observed X(3872) in the $\pi^+\pi^- J/\psi$ channel in the $B \rightarrow K\pi^+\pi^- J/\psi$ decays [26]. The di-pion spectrum looks like a rho meson. In the same experiment, a sharp $\psi'$ signal was also observed.

Later it was also observed in the $\pi^+\pi^-\pi^0 J/\psi$ mode [27]. The three pion spectrum peaks around a virtual omega meson. According to PDG [4], its mass is $3871.2 \pm 0.54$ MeV and width less than 2.3 MeV, which is the typical detector resolution. It’s important to note that the $\rho J/\psi$ decay mode violates isospin symmetry!
Both CDF and D0 collaborations confirmed X(3872) in the $\pi^+\pi^- J/\psi$ channel in the proton anti-proton collision [28,29]. Again the di-pion spectrum looks like a rho meson [32] and a very clear $\psi'$ signal was observed in the same experiments. In other words, the production properties of X(3872) are very similar to those of $\psi'$, which is a pure charmonium state.

Both Babar and Belle collaboration observed the radiative decay mode $X(3872) \rightarrow \gamma J/\psi$ [27,33]. Therefore the C-parity of X(3872) is even. From angular correlations of final states, Belle collaboration ruled out the $0^{++}$ and $0^{-+}$ possibilities and favors the $1^{++}$ assignment [34]. The analysis of CDF collaborations allows only $1^{++}$ and $2^{-+}$ [35]. Hence the quantum number of X(3872) is probably $1^{++}$. But the $2^{-+}$ possibility is not ruled out by experiments.

There are theoretical arguments against the $2^{-+}$ possibility in the non-relativistic quark model [36]. Since the $2^{-+}$ charmonium is the spin-singlet D-wave state and $J/\psi$ is the spin-triplet S-wave state, E1 transition $2^{-+} \rightarrow J/\psi \gamma$ is forbidden in the non-relativistic limit. On the other hand, the D-wave radial wave function is orthogonal to the S-wave radial wave function, therefore M1 transition $2^{-+} \rightarrow J/\psi \gamma$ is also forbidden. Belle and Babar collaborations observed the radiative decay mode. Therefore X(3872) is unlikely to be the $2^{-+}$ charmonium. But will relativistic corrections change this picture?

3.4.2. Is X(3872) a molecular state?

X(3872) sits exactly on the $D^0 \bar{D}^{0*}$ threshold and lies very close to the $\rho J/\psi$, $\omega J/\psi$ and $\bar{D}^+ D^{-*}$ thresholds. It is extremely narrow and around 100 MeV below quark model prediction of $\chi_{c1}$. Its hidden charm modes are quite important while the $\rho J/\psi$ decay mode violates isospin symmetry. All the above facts stimulated several groups to propose X(3872) could be a molecular state [37,38,39,40,41].

Especially Swanson proposed [40] that X(3872) is mainly a $D^0 \bar{D}^{0*}$ molecule bound by both quark and pion exchange. Its wave function also contains small but important $\rho J/\psi$, $\omega J/\psi$ and $\bar{D}^+ D^{-*}$ components. The molecule picture explains the proximity to the $D^0 \bar{D}^{0*}$ threshold and hidden charm decay modes quite naturally. This model has been very popular.

But experimental evidence against the molecular assignment is accumulating. The radiative decay mode is clean and ideal to test the model. Two experiments measured this ratio. The value from Belle collaboration is [27]

$$\frac{B(X(3872) \rightarrow \gamma J/\psi)}{B(X(3872) \rightarrow \pi^+\pi^- J/\psi)} = 0.14 \pm 0.05$$

and that from Babar collaboration is [33]

$$\frac{B(X(3872) \rightarrow \gamma J/\psi)}{B(X(3872) \rightarrow \pi^+\pi^- J/\psi)} \approx 0.25$$

while the theoretical prediction from the molecular model is 0.007.

Belle collaboration reported a near-threshold enhancement in the $D^0 \bar{D}^{0*} \pi^0$ system with a mass $3875.4 \pm 0.7^{+1.2}_{-2.0}$ MeV [42]. From this measurement

$$\frac{B(X(3872) \rightarrow D^0 \bar{D}^{0*} \pi^0)}{B(X(3872) \rightarrow \pi^+\pi^- J/\psi)} = 9.4^{+3.6}_{-4.3}$$
while the theoretical prediction is less than 0.1. Very recently Babar collaboration observed X(3872) in the $\bar{D}D^*$ invariant mass spectrum with a mass 3875.6 $\pm$ 0.7$^+_{-1.5}$ MeV [43], which agrees with the value from Ref. [42] very well. Such a value is clearly above the $\bar{D}D^*$ threshold and does not support the molecular picture.

3.4.3. Could X(3872) still be a $1^{++}$ charmonium?

Recall that the production properties of X(3872) are similar to those of $\psi'$ and the typical quark model accuracy is around 100 MeV for charmonium states above open-charm decay threshold. Deviation around 100 MeV from quark model prediction may be still acceptable. Very interestingly, a recent lattice simulation by CLQCD collaboration claimed that $\chi'_{c1}$ lies around 3853 MeV [44]. The $1^{++}$ charmonium assignment really deserves serious attention [45,46,1]!

There are three main obstacles of $1^{++}$ charmonium assignment. However, possible solutions exist which I list below:

- Low mass
  - Strong S-wave coupled channel effects may lower its mass?
- Large isospin symmetry breaking $\rho J/\psi$ decay
  - Hidden charm decay can happen through rescattering mechanism [47,48]: $X \rightarrow D^0D'^* + \bar{D}^+D^{-*} \rightarrow \rho J/\psi(\omega J/\psi)$. There is isospin symmetry breaking in the mass of $\bar{D}D^*$ pair since $D^+(D^{-*})$ is heavier than $D^0(D'^*)$. The $\rho J/\psi$ mode has much larger phase space than $\omega J/\psi$ mode since the rho meson is very broad. All the above factors may combine to make a sizable $\rho J/\psi$ decay width.
- Extremely narrow width
  - The total width of X(3875) needs some exotic schemes such as decreasing quark pair creation strength of $3P_0$ model near threshold [49].

4. Y(4260)

BABAR collaboration observed a charmonium state around 4.26 GeV in the $\pi^+\pi^- J/\psi$ channel [50]. Since this resonance is observed in the $e^+e^-$ annihilation through initial state radiation (ISR), its spin-parity is known $J^{PC} = 1^{--}$. Later several other collaborations confirmed Y(4260) [51,52,53,54]. The central values of its mass and width from various measurement ar collected in Table 2.

|            | Babar | CLEO-c | CLEO III | Belle |
|------------|-------|--------|----------|-------|
| Events     | 125   | 50     | 14       | 165   |
| Mass       | 4259  | 4260   | 4283     | 4295  |
| Width      | 88    | 70     | 133      |       |

Table 2
The central values of the extracted mass and width of Y(4260) from various experimental measurements.
However $Y(4260)$ was not seen in the $e^+e^-$ annihilation. In fact, $R$ distribution dips around 4.26 GeV. Its leptonic width is small: $\Gamma(Y \to e^+e^-) < 240$ eV [55] and its hidden charm decay width is large: $\Gamma(Y \to J/\psi\pi\pi) > 1.8$ MeV!

According to the PDG assignment of the $1^{--}$ charmonium, there are four S-wave states $J/\psi$, $\psi(3686)$, $\psi(4040)$, $\psi(4415)$ and two D-wave states $\psi(3770)$, $\psi(4160)$. Naively one would expect the $3^3D_1$ state lying above 4.4 GeV. In other words, there is no suitable place for $Y(4260)$ in the quark model spectrum. All the above states have a sharp peak in $R$ distribution. But $Y(4260)$ has a dip! The discovery of $Y(4260)$ indicates the overpopulation of the $1^{--}$ spectrum if PDG classification of the observed $1^{--}$ charmonium is correct.

From BES and CLEOc’s recent measurement, the hidden charm decay width of $\psi''$: $\Gamma(\psi'' \to J/\psi\pi\pi) \approx 50$ keV [4]. If $Y(4260)$ is a charmonium state, one might expect a comparable $J/\psi\pi\pi$ decay width instead of $\Gamma(Y \to J/\psi\pi\pi) > 1.8$ MeV. Similar di-pion transitions from $\psi(4040)$ or $\psi(4160)$ were not observed in the same experiments. One may wonder whether the conventional charmonium assignment is in trouble.

Virtual photon does not couple to glues directly and glueballs easily decay into light hadrons which were not observed experimentally. So $Y(4260)$ does not look like a glueball.

Although it lies close to $DD_1(2420)$, $DD^*_1$ or $D_0^*(2310)D^*$ thresholds, $Y(4260)$ does not seem to arise from the threshold or coupled-channel effects since the $J/\psi\pi\pi$ spectrum is very symmetric. There is no obvious distortion from nearby thresholds.

Could $Y(4260)$ be a tetraquark? Tetraquark falls apart into $D\bar{D}$ very easily. So $D\bar{D}$ should be one of the dominant decay modes. Its width would be much larger than 90 MeV! Moreover, if the isoscalar component of the photon had produced $Y(4260)$ with $I^G = 0^-$, its isovector component would also have produced $Y''(4260)$ with $I^G = 1^+$, which decays into $J/\psi\pi^+\pi^-\pi^0$. This possibility had been ruled out by Babar collaboration [56]!

Several groups suggested that $Y(4260)$ may be a a hybrid charmonium in 2005 [56,57,58]. Its mass leptonic width, total width, production cross section, decay pattern (hidden charm vs open charm), flavor blind decays into $J/\psi\pi\pi$ and $J/\psi K\bar{K}$, overpopulation of $1^{--}$ spectrum and its large hidden charm decay width satisfy the very naive expectation of a hybrid charmonium state.

It’s very interesting to recall that Quigg and Rosner predicted one $1^{--}$ charmonium state at 4233 MeV using the logarithmic potential thirty years ago, which was identified as the 4S state [59]. In order to study possible effects of color screening and large string tension in heavy quarkonium spectra, Ding, Chao, and Qin also predicted their 4S charmonium state exactly at 4262 MeV twelve years ago [60]! Their potential is quite simple:

$$V(r) = -\frac{4\alpha_s}{3r} + \frac{T}{\mu}(1 - e^{-\mu r})$$

(7)

where $T$ is the string tension and $\mu$ is the screening parameter. With such a perfect agreement, one may wonder whether PDG assignment misses one $1^{--}$ charmonium state in the quark model. Or does the same traditional quark potential hold for higher states far above strong decay threshold? However, two serious challenges remain for the conventional quark model interpretation: (1) how to generate the huge $J/\psi\pi\pi$ decay width? (2) How to explain the dip in the $R$ distribution?
5. Summary

After four years' extensive theoretical and experimental efforts, the situation of $D_{s j}$ mesons is almost clear: both $D_{s0}^*(2317)$ and $D_{s1}^*(2460)$ are probably $c\bar{s}$ states. But the higher charmonium sector is still very controversial
- $Z(3930)$ is very probably $\chi^\prime_{c2}$
- $X(3940)$ may be $\eta_c^\prime$
- $Y(3940)$ needs confirmation
- $X(3872)$ may be a candidate of $\chi_{cJ}^J$ (or molecule)
- $Y(4260)$ may be a candidate of hybrid charmonium (or charmonium).

BESIII in Beijing will start taking data this year and will increase its database by 100 times. Jlab, B factories and other facilities are increasing the database continuously. J-PARC will start running at the end of next year. There will be great progress in the search of non-conventional hadrons and more unexpected...

Acknowledgment

The author thanks the organizers of the international nuclear physics conference 2007 for their kind invitation. This project was supported by the National Natural Science Foundation of China under Grants 10421503 and 10625521, and Ministry of Education of China, FANEDD.

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