Charmonium Spectrum and New Observed States

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Abstract

The linearity and parallelism of Regge trajectories is combined with a hyperfine splitting relation in multiplet to study charmonium spectrum. It is found that predictions to the spectrum of 1D multiplet could be made once another 1D state is confirmed. The newly observed $X(3872)$, $Y(3940)$, $X(3940)$, $Y(4260)$ and $Z(3930)$ are studied within the charmonium framework.

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The exploration of hadron spectrum is a central issue in nonperturbative QCD. Charmonium is the most suitable system to be studied for its non-relativistic features and a large number of data accumulated in experiments. It provides people fruitful information to study the properties of strong interaction. As well known, $q\bar{q}$ interaction is described well in terms of potentials including a color Coulombic $\sim 1/r$ potential, a confinement potential and some small corrections. However, the exact form of strong interaction between quark and anti-quark in hadrons is not clear, the nature of confinement and the relation of the potentials to QCD are not clear either. All these properties are expected to be detectable from the hadron spectrum. Furthermore, the study of charmonium spectrum will be helpful both to identify observed states and to find new states. Since the discovery of $J/\psi$, many states have been discovered and identified in charmonium family. In particular, some new charmonium or charmonium-like states have lately been observed. This recent achievement in experiments has stimulated people’s great interests on this important field once again.

$h_c(^1P_1)$ was identified by CLEO[1] in the isospin-violating reaction

$$e^+e^- \rightarrow \psi(2s) \rightarrow \pi^0 h_c, h_c \rightarrow \gamma \eta_c.$$  

$X(3872)$ was first observed by Belle[2] in exclusive B decays

$$B^\pm \rightarrow K^\pm X(3872), X(3872) \rightarrow \pi^+\pi^- J/\psi$$

with $M = 3872.0 \pm 0.6(stat) \pm 0.5(syst)$ MeV and $\Gamma < 2.3$ MeV(90% C.L.). This state is then confirmed by CDF II[3], D0[4] and BaBar[5].

$Y(3940)$ was observed by Belle[6] in exclusive B decays

$$B \rightarrow KY(3940), Y(3940) \rightarrow \omega J/\psi.$$  

If this enhancement is treated as an S-wave Breit-Wigner resonance, its mass and total width are $M = 3943 \pm 11 \pm 13$ MeV and $\Gamma = 87 \pm 22 \pm 26$ MeV. $X(3940)$ was observed by Belle[7] in

$$e^+e^- \rightarrow J/\psi X(3940), X(3940) \rightarrow D^*\bar{D}$$

with $M = 3943 \pm 6 \pm 6$ MeV and $\Gamma < 52$ MeV at 90% C. L.

$Y(4260)$ was observed by BaBar[8] in initial-state radiation events,

$$e^+e^- \rightarrow \gamma_{ISR} Y(4260), Y(4260) \rightarrow \pi^+\pi^- J/\psi.$$
with $M \sim 4.26$ GeV and $\Gamma \sim 90$ MeV. This state of $\pi^+\pi^- J/\psi$ was confirmed recently by CLEO collaboration\[10\]. The channels $Y(4260) \rightarrow \pi^0\pi^0 J/\psi$ and $Y(4260) \rightarrow K^+K^- J/\psi$ have also been observed in their study.

$Z(3930)$ was observed in the process $\gamma\gamma \rightarrow D\bar{D}$ by Belle collaboration\[9\] with $M = 3929\pm5\pm2$ MeV and $\Gamma = 29\pm10\pm2$ MeV, respectively. The states $X(3940)$, $Y(3940)$ and $Z(3930)$ have just been observed in single experiment so far and require confirmation by more experiments.

There are many interpretations and suggestions to these new states since the first announcement of $X(3872)$. For example, interpretations to the $X(3872)$ could be found in \[11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21\] and interpretations to the $Y(4260)$ could be found in \[22, 23, 24, 25, 26, 27, 28\]. Some systemic analyzes to these newly observed states could be found in \[29, 30, 31\]. For the limit of pages, only parts of literatures are listed here.

The interpretations include conventional charmonium arrangement and other exotic arrangements outside the $q\bar{q}$ framework such as the molecule state, the tetraquark state, the hybrid or the mixing state among them. However, the identification of these states, especially the $X(3872)$, is still an open topic.

In order to identify all these states, it is necessary for people to know well both convenient hadron and exotic hadron. At present time, people is far away from this. In view of this complexity, we will study the spectrum of these states within the charmonium framework, while put aside their exotic interpretations and complicated production and decay properties.

Hadron spectrum has been studied phenomenologically with Regge trajectory theory for a long time. Regge trajectory theory indicates a relation of the square of the hadron masses and the spin of the hadrons. A Regge trajectory is a line in a Chew-Frautschi\[32\] plot representing the spin of the lightest particles versus their mass square, $t$:

$$\alpha(t) = \alpha(0) + \alpha' t$$

where intercept $\alpha(0)$ and slope $\alpha'$ depend weekly on the flavor content of the states lying on corresponding trajectory. For light quark mesons, $\alpha' \approx 0.9$ GeV$^{-2}$.

For radial excited light $q\bar{q}$ mesons, trajectory on $(n, M^2)$-plots is described by\[33\]

$$M^2 = M_0^2 + (n - 1)\mu^2,$$
where $M_0$ is the mass of basic meson, $n$ is the radial quantum number, and $\mu^2$ (approximately the same for all trajectories) is the slope parameter of the trajectory.

The behaviors of Regge trajectories in different system, which indicate that a Regge trajectory is approximately linear while different trajectories are approximately parallel, have been studied phenomenologically in many literatures. Regge trajectory with neighboring mesons (opposite $PC$) stepped by 1 in $J$ was first found to be linear and parallel, but was subsequently found to deviate from linearity and parallelism \[34, 35\]. In this case, the exchange degeneracy applies not well. In phenomenology, the exact deviation depends on peculiar family of mesons, baryons, glueballs, hybrids and energy regime. In theory, the non-linearity and the non-parallelism of Regge trajectory result from intrinsic quark-gluon dynamics which may be flavor and $J$ dependent. Some detailed studies of Regge trajectories could be found in many more fundamental theories\[37\].

In fact, once Regge trajectories with neighboring mesons (same $PC$) stepped by 2 in $J$ are under consideration, the linearity and the parallelism of these trajectories keep well \[33, 34, 36\], which means that the exchange degeneracy applies.

Hadron spectroscopy has also been explored in many other models\[38, 39, 40, 41, 42, 43\] based on QCD. In these models, the spectrum of charmonium has been excellently reproduced for the nonrelativistic features of this system. An interesting conclusion is that some hyperfine splitting relations are predicted to exist among the members in a multiplet in potential models\[44, 45, 46\]. The S-wave hyperfine splitting (spin-triplet and spin-singlet splitting), $\Delta M_{hf}(nS) = M(n^3S_1) - M(n^1S_0)$, is predicted to be finite. For experimentally observed $M(\psi)$ and $M(\eta_c)$\[47\],

\[
\Delta M_{hf}(1S) = M(J/\psi) - M(\eta_c) \simeq 115 \pm 2 \text{ MeV}, \\
\Delta M_{hf}(2S) = M(\psi(2S)) - M(\eta_c(2S)) \simeq 43 \pm 3 \text{ MeV}.
\]

The hyperfine splitting of P-wave or higher L-state is predicted to be zero

\[
\Delta M_{hf}(1P) = \langle M(1^3P_J) > - M(1^1P_1) \approx 0, \\
\Delta M_{hf}(1D) = \langle M(1^3D_J) > - M(1^1D_2) \approx 0,
\] (3)

where the deviation from zero is no more than a few MeV. Though the exact form of potentials may be different in different potential models, these
Theoretical predictions are the same. The most important fact is that the relation in the $1P$ charmonium multiplet has been proved to be obeyed in a high degree accuracy\cite{48}. In this paper, these relations in the $1P$ and $1D$ multiplets will be used as facts (or assumptions).

In constituent quark model, $q\bar{q}$ mesons could be marked by their quantum numbers, $n^{2S+1}L_J$. For quarkonia, the quantum numbers $PC$ are determined by $P = (-1)^{L+1}$ and $C = (-1)^{L+S}$. From PDG\cite{48}, we get table 1 for charmonium mesons without radial excitation. In this table, entries in the first volume are observed states, entries under $J^PC$, $n^{2S+1}L_J$ and mass are confirmed or favored assignment by theoretical analyzes based on experiments. Entries in the last volume are information from PDG, and the states marked with a “?” are those not confirmed and omitted from the summary table. Mass of the most lately identified $h_c(1P)$ by CLEO\cite{1}(M = 3524.4 ± 0.6 ± 0.4 MeV) is not filled in the table.

Except for the $1^{--} n^3S_1$ states, there is no excited charmonium having been definitely identified so far. From PDG and some recent assumptions, we obtain table 2. In the table, $Z(3930)$ was suggested as the $\chi_{c2}(2P)$\cite{9}, and $Y(3940)$ was suggested as $3^1S_0$\cite{30} or $2^3P_0$\cite{49}.

After filling in these two tables, we proceed firstly with the study of

| States      | $J^PC$ | $n^{2S+1}L_J$ | Mass(MeV) | Note              |
|-------------|--------|---------------|-----------|-------------------|
| $\eta_c(1S)$ | 0++    | $1^3S_0$      | 2979.6    | PDG               |
| $J/\psi(1S)$ | 1--    | $1^3S_1$      | 3096.9    | PDG               |
| $\chi_{c0}(1P)$ | 0++    | $1^3P_0$      | 3415.2    | PDG               |
| $\chi_{c1}(1P)$ | 1++    | $1^3P_1$      | 3510.6    | PDG               |
| $h_c(1P)$    | 1++    | $1^3P_1$      | 3526.2    | PDG ($J^PC = ???$) |
| $\chi_{c2}(1P)$ | 2++    | $1^3P_2$      | 3556.3    | PDG               |
| $\psi(3770)$ | 1--    | $1^3D_1$      | 3769.9    | PDG               |
| $\psi(3836)$ | 2--    | $1^3D_2$      | 3836 ± 13 | PDG (?)           |
| ?            | 2++    | $1^3D_2$      | ?         | ?                 |
| ?            | 3--    | $1^3D_3$      | X(3872)?  | × this work       |
| ?            | 2++    | $1^3F_2$      | ?         | ?                 |
| ?            | 3++    | $1^3F_3$      | ?         | ?                 |
| ?            | 3++    | $1^3F_3$      | ?         | ?                 |
| ?            | 4++    | $1^3F_4$      | ?         | ?                 |

Table 1: Spectrum of charmonium without radial excitation.
| States         | $J^{PC}$ | $n^{2S+1}L_J$ | Mass(MeV)   | Note    |
|---------------|----------|---------------|-------------|---------|
| $\eta_c(1S)$  | 0--      | $1^1S_0$      | 2979.6      | PDG     |
| $\eta_c(2S)$  | 0--      | $2^1S_0$      | 3654 ± 6 ± 8| PDG(?)  |
| $\eta_c(3S)$  | 0--      | $3^1S_0$      | Y(3940)?    |         |
| $J/\psi(1S)$  | 1--      | $1^3S_1$      | 3096.9      | PDG     |
| $\psi(2S)$    | 1--      | $2^3S_1$      | 3686.1      | PDG     |
| $\psi(4040)$  | 1--      | $3^3S_1$      | 4040 ± 10   | PDG     |
| $\psi(4415)$  | 1--      | $4^3S_1$      | 4415 ± 6    | PDG     |
| $\chi_{c0}(1P)$ | 0++     | $1^3P_0$      | 3415.2      | PDG     |
| $\chi_{c0}(2P)$ | 0++     | $2^3P_0$      | Y(3940)?    | [49]    |
| $\chi_{c1}(1P)$ | 1++     | $1^3P_1$      | 3510.6      | PDG     |
| $\chi_{c1}(2P)$ | 1++     | $2^3P_1$      | X(3872)?    | ?       |
| $h_c(1P)$     | 1++      | $1^1P_1$      | 3526.2      | PDG ( $J^{PC}=?$) |
| $h_c(2P)$     | 1++      | $2^1P_1$      | ?           | ?       |
| $\chi_{c2}(1P)$ | 2++     | $1^3P_2$      | 3556.3      | PDG     |
| $\chi_{c2}(2P)$ | 2++     | $2^3P_2$      | Z(3930)     | [6]     |
| $\psi(3770)$  | 1--      | $1^3D_1$      | 3770        | PDG     |
| $\psi(4160)$  | 1--      | $2^3D_1$      | 4159 ± 20   | PDG     |
| $Y(4260)$     | 1--      | $3^3D_1$      | 4260?       | ?       |

Table 2: Spectrum of charmonium with different radial n.
properties of relevant Regge trajectories.

For states without radial excitation, states in each group below make a trajectory

\[
\begin{align*}
0^- (1^1S_0), & \quad 1^+ - (1^1P_1), & \quad 2^- (1^3D_2), & \quad \cdots, \\
1^- (3^3S_1), & \quad 2^{++} (3^3P_2), & \quad 3^- (3^3D_3), & \quad \cdots, \\
0^{++} (3^3P_0), & \quad 1^{--} (3^3D_1), & \quad 2^{++} (3^3F_2), & \quad \cdots, \\
1^{++} (3^3P_1), & \quad 2^{--} (3^3D_2), & \quad 3^{++} (3^3F_3), & \quad \cdots.
\end{align*}
\]

These trajectories were analyzed also in a recent work [49].

The high excitation states appeared in these trajectories have not been observed. In terms of the first two states in each trajectory, their rough slopes \( \alpha' \) are determined

\[0.282, 0.327, 0.392, 0.419 \text{ GeV}^{-2},\]

respectively. The slopes of these trajectories increase slowly. Obviously, these trajectories are not straightly parallel, and the exchange degeneracy applies not well. These Regge trajectories indeed fan out as pointed out in reference [34].

For states with radial excitation, the situation is not so satisfactory for lack of experimental data. At present, there isn’t enough data to make a trajectory even with neighboring mesons stepped by 1 in \( J \). However, if more states are pinned down, they will consist of some new Regge trajectories.

Once the \( Z(3930) \) is confirmed as the \( 2^{++} \chi_{c2}(2P) \) [9], the \( 1^{--} 2^3S_1 \) and the \( 2^{++} 2^3P_2 \) will make an excited trajectory. The slope \( \alpha' = 0.540 \text{ GeV}^{-2} \) is larger than the corresponding one (\( \alpha' = 0.327 \text{ GeV}^{-2} \)) without radial excitation.

If the suggestion of \( Y(3940) \) in [49] is right, the \( 0^{++} 2^3P_0 \) and the \( 1^{--} 2^3D_1 \) will make an excited trajectory with slope \( \alpha' = 0.564 \text{ GeV}^{-2} \), which is also larger than the corresponding one (\( \alpha' = 0.392 \text{ GeV}^{-2} \)) without radial excitation.

The favorable quantum numbers for \( X(3872) \) is now believed to be \( J^{PC} = 1^{++} \) or \( 2^{-+} \) [50]. If \( X(3872) \) is the candidate for \( 2^- 2^1D_2 \) state, the \( 0^{--} 2^3S_0 \) and the \( 2^{-} 2^1D_2 \) will make an excited Regge trajectory with slope \( \alpha' = 1.219 \text{ GeV}^{-2} \). If \( X(3872) \) is the radial excited \( 1^{++} 2^3P_1 \) charmonium, it makes another trajectory with the unknown \( 2^{--} 2^3D_2 \).
After we have an overall understanding of the properties of Regge trajectories for charmonium, we start our analyzes to the newly observed states, and give some predictions to the spectrum of the $1\cal D$ multiplet.

From previous statements and our analyzes, Regge trajectories with neighboring mesons stepped by 1 in $J$ really deviate from linearity and parallelism. The worst thing is that we don’t know how large the deviations from the linearity and parallelism are for these trajectories. Though we can give a rough analysis and predictions to the charmonium spectrum in terms of the trajectory with neighboring mesons stepped by 1 in $J$ as did in [49], we have no such an intention to go ahead in this Letter.

In order to make a more precise analysis and potential predictions, we should make use of the linearity and parallelism for trajectories with neighboring mesons stepped by 2 in $J$. Unfortunately, there exists no Regge trajectory with neighboring mesons stepped by 2 in $J$ from experimental data in table 1 and table 2. However, if the linearity and parallelism of Regge trajectories with neighboring mesons stepped by 2 in $J$ (all mesons with the same $PC$ in one trajectory) is combined with the hyperfine splitting relation of $P$-wave or higher $L$-state charmonium, some predictions to the spectrum of the $1D$ charmonium multiplet could be obviously made.

The two lowest Regge trajectories with neighboring mesons stepped by 2 in $J$ consist of

$$\begin{align*}
0^- + (1S_0), & \quad 2^- + (1D_2), \\
1^- - (3S_1), & \quad 3^- - (3D_3).
\end{align*}$$

These two trajectories should be parallel and have the same slope. In these trajectories, it is well known that $0^- + \eta_c(1S)$ and $1^- - \psi(3770)$ have been identified, while $2^- + 1^1D_2$ and $3^- - 1^3D_3$ have not been pinned down.

In the $1D$ multiplet, the $1^- - \psi(3770)$ is identified, while other three states have not been identified. From our analyzes, if another $1D$ state ($2^- - 2^+$ or $3^- - 3^+$) is confirmed, the total spectrum of the $1D$ multiplet could be predicted.

The favored assignment to $\psi(3836)$ is the $1^3D_2$ state [48], which has not been definitely confirmed. If $\psi(3836)$ is really confirmed as the $2^- - 1^3D_2$ state, the masses of $3^- - 1^3D_3$ and $2^+ - 1^1D_2$ could be predicted as follows.

When the mass of $3^- - 1^3D_3$ is set to be $M$ GeV, the mass of $2^+ - 1^1D_2$ is found to be $(7M + 5 \times 3.836 + 3 \times 3.770)/15$ GeV due to zero of hyperfine splitting of the $1D$ charmonium. On the other hand, these two Regge
trajectories have the same slope. Therefore, an equation with $M$ is obtained

$$M^2 - 3.097^2 = \left( \frac{7M + 5 \times 3.836 + 3 \times 3.770}{15} \right)^2 - 2.98^2. \tag{4}$$

The solution to this equation is $M = 3.981 \text{ GeV}$. Correspondingly, the mass of $2^{-+} 1^1D_2$ is predicted to be 3.890 GeV.

Within the charmonium framework, $X(3872)$ was ever interpreted as the $1^3D_2$ and $1^3D_3[51]$. These arrangements could also be checked.

If $X(3872)$ is really the $2^{-+} 1^3D_2$ state, a similar equation

$$M^2 - 3.097^2 = \left( \frac{7M + 5 \times 3.872 + 3 \times 3.770}{15} \right)^2 - 2.98^2 \tag{5}$$

with $M$ being the mass of $3^{-} 1^3D_3$ is obtained. The masses of the $3^{-} 1^3D_3$ and the $2^{-+} 1^1D_2$ are therefore found to be 4.002 GeV and 3.912 GeV, respectively.

If $X(3872)$ is the $3^{-} 1^3D_3$, the relations in this $1D$ multiplet do not respect the parallelism of Regge trajectory and hyperfine splitting relation. The breaking of hyperfine splitting relation is quite large even though a large deviation from the parallelism of Regge trajectory is assumed. So we can conclude safely that this arrangement is impossible and should be ruled out. This viewpoint is supported by a recent experimental analysis[50] where the interpretation of $3^{-} 1^3D_3$ seems to be excluded.

In any case of these arrangements, once another new state in the $1D$ multiplet is definitely pinned down, the masses of another two states will be determined. Obviously, no matter which case is the reality, it is important to identify another new state in the $1D$ multiplet firstly, and then to find another two states in the relevant energy regime. Of course, if $X(3872)$ is the $2^{-+} 1^3D_2$ state, the existed $\psi(3836)$ requires other interpretation.

In this Letter, the properties of Regge trajectories of charmonium are studied. We combined the linearity and parallelism of Regge trajectories with a hyperfine splitting relation, and observed that some predictions could be given to the spectrum of the $1D$ multiplet. From these analyzes, some results on charmonium spectrum have been obtained:

1. The assignment of $X(3872)$ as the $3^{-} 1^3D_3$ charmonium state should be ruled out.
2. If the $X(3872)$ is the $2^{-+} 1^3D_2$ state, the masses of the $3^{-} 1^3D_3$ and the $2^{-+} 1^1D_2$ are predicted to be 4002 MeV and 3912 MeV, respectively.
3. The definite confirmation of $\psi(3836)$ is important for the $1D$ multiplet. If it is confirmed as the $2^{--} 1^{3}D_2$ state, the masses of the $3^{--} 1^{3}D_3$ and the $2^{++} 1^{1}D_2$ is predicted to be 3981 MeV and 3890 MeV, respectively. These theoretical predictions are expected to give some hints to the forthcoming experiments. As well known, the linearity and the parallelism of Regge trajectories with neighboring mesons stepped by 2 in $J$ were obtained in the analyzes to many mesons system in literatures, slight deviations were observed also. The deviations are expected to affect our conclusions little for their smallness. However, it will be still interesting to detect how large the deviations are in charmonium, especially, their relations to the spin-spin and spin-obit interactions in hadron. The phenomenological study of the deviations may be important for the study of potential models.

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