Charmonium possibility of $X(3872)$

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Properties of Regge trajectories for charmonium are studied. Possible interpretations and their implications to newly observed $X(3872)$ are examined. It is found that the mass of $X(3872)$ is consistent with the $1^{++} 2^3P_1$ and the $2^{−+} 1^1D_2$ charmonium states.

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I. INTRODUCTION

Recently some new charmonium or charmonium-like states, such as $X(3872)$ $\bar{1}$ 2 3 4 5, $Y(3940)$ 6, $X(3940)$ 7, $Y(4260)$ 8, 9 and $Z(3930)$ 10 were observed. $Z(3930)$ was pinned down as the $\chi_{c2}(2p)$ in 2006 PDG 11, while others have not been identified. Among these new states, $X(3872)$ has drawn people’s great interest for its peculiar decay properties. $X(3872)$ was first observed by Belle 1 in exclusive B decays,

$$B^\pm \to K^\pm X(3872), \quad X(3872) \to \pi^+\pi^-J/\psi.$$  
(1)

Subsequently it was confirmed by CDF 2, 5, 6, D0 4 and BaBar 3. The mass of this state is $M = 3871.2 \pm 0.5$ MeV and the width $\Gamma < 2.3$ MeV(0.9 C.L.). The mass is within errors at the $D^0\bar{D}^{*0}$ threshold, but the width is small.

To accommodate $X(3872)$ in hadron spectroscopy, considerable speculations and plenty of interpretations were proposed. There are conventional $c\bar{c}$ charmonium assignments 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, molecule state interpretations 12, 22, 23, 24, 25, tetraquark state interpretations 26, hybrid interpretations 27 or mixing states interpretations among them 24, 22, 28, 29.

Features of hadron were mainly exhibited through its production and decay properties. Four decay modes of $X(3872)$ have already been observed. $X(3872) \to J/\psi\rho$ 1, 30 and $X(3872) \to J/\psi\omega$ 31, 32 were observed by Belle, $X(3872) \to J/\psi\omega$ was observed by BaBar 31 and BaBar 32. Recently, $B \to D^{0}\bar{D}^{*0}\pi^0K$ was observed by Belle 33.

Possible $J^{PC}$ of $X(3872)$ have been suggested through these decay modes. The observation of $X(3872) \to J/\psi\rho$ indicates that its $C = +$. Analysis of angular distribution in $X(3872) \to J/\psi\rho$ favors its $J^{PC} = 1^{++}$ 34. This assignment is also supported by the observation $B \to D^{0}\bar{D}^{*0}\pi^0K$ 33. However, some analyses suggest that both $1^{++}$ and $2^{−+}$ are possible 2, 33.

As for the nature of $X(3872)$, none of the speculations is favored. In the discovery mode observed by Belle 1, $X(3872)$ was naturally expected to be the $1^{++} 2^3P_1$ or the $2^{−+} 1^1D_2$ charmonium state due to its decay final states. However, there are difficulties in the charmonium explanations. $X(3872)$ seems not match any predicted charmonium state for its lower mass, narrower width and puzzling decay properties. The upper limit for the radiative transition $X(3872) \to \gamma\chi_{c1}$ set by Belle 1 makes it difficult to identify $X(3872)$ with any charmonium state. The simultaneous decay of $X(3872) \to J/\psi\rho$ 1 and $J/\psi\omega$ 31, 32, with roughly equal branching ratios is a strong implication of the ”molecule” state assignment for $X(3872)$ 24, 25.

If $X(3872)$ is a ”molecule” or tetraquark state, there are also difficulties. The observed branching fraction of $X(3872) \to \gamma J/\psi$ 31, 32 is much larger than theoretically predicted one for molecule states 24. In particular, if the near-threshold enhancement in $B \to D^{0}\bar{D}^{*0}\pi^0K$ 33 is due to $X(3872)$, this mode has a branching ratio $9.4_{-4.3}^{+3.6}$ times larger than $B(B^+ \to X(3872)K^+) \times B(X(3872) \to J/\psi\pi^+\pi^-)$. This mode appears to be dominant and the branching ratio is much larger than the predicted one in the molecule model.

So far, there is no compelling evidence to confirm one interpretation or to exclude one interpretation, more decay modes have to be searched and studied. Recently, the radiative $X \to DD\gamma$ decay mode was suggested 33, 36.

In the charmonium explanation of $X(3872)$, one difficulty is its lower mass. In quark models, $1^{++} 2^3P_1$ was expected to have mass $\sim 3953$ MeV in Ref. 38 and $\sim 3929$ MeV in Ref. 39. In general, features of charmonium are described well by quark models (where the quark dynamics was assumed) 40. In lattice, the spectrum of charmonium was computed also 41. However, the exact quark dynamics in hadron is not very clear, and lattice results may be improved. Whether $X(3872)$ really has the lower mass difficulty requires more phenomenological examinations.

Recently, charmonium spectrum were analyzed in terms of Regge trajectory theory 42, 43. However, the analyses were not complete for limited experimental information at that time. With more experimental information in hand (the $J^{PC}$ of $X(3872)$ is believed to be $1^{++}$ or $2^{−+}$ at present time), we can continue a further exploration of the charmonium possibility of $X(3872)$ and its implication through its mass relations with other charmonium states in this Letter.

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II. REGGE Trajectory and Hyperfine Splitting of Charmonium

Regge trajectory [14, 15] is an important phenomenological way to describe the masses relations among different hadrons. There is resurgent interest in Regge theory for much more accumulated experimental data. Furthermore, some quark models need more complete experimental fits for testing [46]. Regge trajectories are some graphs of the total quantum numbers $J$ versus mass squared $M^2$ over a set of particles which have fixed principal quantum number $n$, isospin $I$, dimensionality of the symmetry group $D$ and flavors. A Chew-Frautschi Regge trajectory is a line:

$$J(M^2) = \alpha(0) + \alpha' M^2,$$

where intercept $\alpha(0)$ and slope $\alpha'$ depend weakly on the flavor content of the states lying on corresponding trajectory. For light quark mesons, $\alpha' \approx 0.9 \text{ GeV}^{-2}$. Different Regge trajectories are approximately parallel.

It is found that the linearity and parallelism of Regge trajectories with neighborhood mesons stepped by 1 in $J$ with opposite $PC$ holds not well [47, 48, 49]. The intrinsic quark-gluon dynamics may result in large non-linearity and non-parallelism of such Regge trajectories. However, the linearity and parallelism of Regge trajectories with neighborhood mesons stepped by 2 in $J$ with the same $PC$ is found to hold well [50].

In addition to these properties of the Regge trajectories with the same principle quantum number $n$, another relation for Regge trajectories with different $n$ was assumed. It was argued that the parallelism of Regge trajectories with different $n$ (others are identical) may hold because of the similar dynamics in hadron [46]. Whether this parallelism of Regge trajectory holds has not been tested for the lack of data.

For radial excited light $q\bar{q}$ mesons, there exist relations between their masses and principle quantum numbers $n$. These mesons consist of another kind of trajectory on $(n, M^2)$-plots [50]

$$M^2 = M_0^2 + (n - 1)\mu^2,$$

where $\mu^2$ is the slope parameter (approximately the same for all trajectories).

Hyperfine (spin-triplet and spin-singlet) splitting relation is another important mass relation among hadrons. In many potential models [51, 52, 53], the S-wave hyperfine (spin-triplet and spin-singlet) splitting, $\Delta M_{hf}(nS) = M(n^3S_1) - M(n^1S_0)$, is predicted to be finite, while other hyperfine splitting of P-wave or higher L-state is expected to be zero:

$$\Delta M_{hf}(1P) = < M(1^3P_2) > - M(1^1P_1) \approx 0,$$

$$\Delta M_{hf}(1D) = < M(1^3D_2) > - M(1^1D_2) \approx 0,$$

where the deviation from zero is no more than a few MeV. Though these predictions are model dependent, the masses relation of the $1P$ charmonium multiplet has been proved to hold in a high degree accuracy [11]. These hyperfine splitting relations of the $1P, 1D$ and $2D$ multiplets will be used as facts (or assumptions).

These mass relations will be studied or used to explore the charmonium spectrum. The paper is organized as follows. In the third section, in terms of the experimental data, all the properties of possible Regge trajectories for the charmonium are studied, and an updated phenomenological analysis is made to the new states. Subsequently, the linearity and parallelism of Regge trajectories with neighborhood mesons stepped by 2 in $J$ is combined with the hyperfine splitting relations of D-wave multiplets to examine some possible charmonium arrangements to $X(3872)$. Then we analyze $X(3872)$ through the observed trajectory property on $(n, M^2)$-plots. Some conclusions and discussions are given in the last section.

III. $c\bar{c}$ Possibility of $X(3872)$

In constituent quark model, $q\bar{q}$ mesons could be marked by their quantum numbers, $n^2S_{1+}L_J$, and the quantum numbers $PC$ of quarkonia are determined by $P = (-1)^{L+1}$ and $C = (-1)^{L+S}$. With the most new data for charmonium mesons [11], we get Table I in this table, the observed states are listed in the first volume, experimentally confirmed or favorable theoretical assignment of $J^{PC}, n^2S_{1+}L_J$ and masses to these states are put in the sequential three volumes. Entries in the last volume are information from PDG, and the states marked with a “?” are those not confirmed or omitted from the summary table.

With this table in hand, we can construct different possible Regge trajectories, study their properties, and proceed with our analysis of $X(3872)$.

As we know, confirmed states in each group below construct a trajectory

$$0^{--}(1^3S_0), \quad 1^{+-}(1^1P_1)$$

$$0^{++}(1^3P_0), \quad 1^{--}(1^3D_1),$$

respectively.

This two trajectories is shown in Fig.1. In the figure, the slope of line 1 is 2.558 GeV$^2$, the slope of line 2 is 3.552 GeV$^2$. It’s obvious that the two trajectories are not parallel. Once the parallelism of this two trajectories is assumed, a large deviation (e.g., $\psi(3770)$ has 0.130 GeV deviation from the “ideal” $1^{+-}(1^1P_1)$ state) would appear.

Another two trajectories with different $n$ are constructed by $J/\psi(1S), \chi_{c2}(1P)$ and radial excited $\psi(2S), \chi_{c2}(2P)$, respectively,

$$1^{--} 1^3S_1, \quad 2^{++} 1^3P_2$$

$$1^{--} 2^3S_1, \quad 2^{++} 2^3P_2.$$
FIG. 1: Existed trajectories of charmonium singlet and triplet

\[
\begin{align*}
J/\psi(1S) & : 1^{- -} 1^S_0 & 3096.9 & \text{PDG} \\
\psi(2S) & : 1^{- -} 2^S_0 & 3638 \pm 4 & \text{QN are predictions} \\
\psi(3770) & : 1^{- -} 3^S_0 & ? & ? \\
\psi(4040) & : 1^{--} 3^S_1 & 4039 \pm 1 & \text{PDG} \\
\psi(4160) & : 1^{--} 4^S_1 & 4421 \pm 4 & \text{PDG} \\
\rho(1S) & : 0^{++} 1^P_0 & 3414.8 & \text{PDG} \\
\rho(2S) & : 0^{++} 2^P_0 & ? & ? \\
\chi_c(1P) & : 1^{++} 1^P_1 & 3510.7 & \text{PDG} \\
\chi_c(2P) & : 1^{++} 2^P_1 & ? & ? \\
\eta(1P) & : 1^{- -} 1^P_1 & 3525.9 & \text{PDG} (?, J^{PC} = 2^{--}) \\
\eta(2P) & : 1^{--} 2^P_1 & ? & ? \\
\chi_c(1P) & : 2^{++} 1^P_2 & 3556.2 & \text{PDG} \\
\chi_c(2P) & : 2^{++} 2^P_2 & 3929 \pm 5 \pm 2 & \text{PDG} \\
\psi(3770) & : 1^{--} 1^D_1 & 3771.1 & \text{PDG} \\
\psi(4160) & : 1^{--} 2^D_1 & 4153 \pm 3 & \text{PDG} \\
\psi(3970) & : 1^{--} 3^D_1 & ? & ? \\
\psi(4260) & : 1^{--} 4^D_1 & ? & ? \\
X(3872) & : ?^+/^\mp ? & 3871.2 & \text{PDG} \\
Y(3940) & : ?^+/^\mp ? & 3943 \pm 11 \pm 13 & \text{PDG (?)} \\
Y(4260) & : 1^{--} ? & 4259 \pm 8^{+2}_{-5} & \text{PDG (?)} \\
\end{align*}
\]

TABLE I: Spectrum of charmonium.

FIG. 2: Existed trajectories of Charmonium triplets with \( n = 1 \) and \( n = 2 \).

The slope of line 1 is 1.850 GeV\(^2\), the slope of line 2 is 3.054 GeV\(^2\). The discrimination of this two slopes is obvious, two trajectories are not parallel. The deviation of \( \chi_{c2}(2P) \) from the “ideal” \( 2^{++} 2^1P_2 \) is about 0.150 GeV. Obviously, the assumption in Ref. [40] that the parallelism of Regge trajectories with different \( n \) may hold works not well for charmonium. In fact, even though the dynamics in hadrons with different \( n \) is similar, the parallelism cannot be deduced directly.

In short, trajectories of charmonium in \((M^2, J)\)-plots with neighborhood mesons stepped by 1 in \( J \) are really not parallel, and they “fan in” [40]. Therefore, the use of the parallelism of these trajectories to predict new states is not reliable if the deviations are unknown.

There exist other Regge trajectories with neighborhood charmonium stepped by 2 in \( J \). According to Ref. [50], the linearity and parallelism of this kind of Regge trajectories was found to hold well. This feature of Regge trajectories for charmonium has not been tested for the lack of experimental data, it could not give more predictions either if this feature is used separately. However, once it is combined with the hyperfine splitting relation in a multiplet, the \( 2^{++} (1^{1}D_2 \text{ or } 2^{1}D_2) \) charmonium possibility of \( X(3872) \) could be examined.

Firstly, let us examine the \( 2^{++} 1^{1}D_2 \) possibility of \( X(3872) \). In theory, states below construct two Regge trajectories

\[
\begin{align*}
0^{++} & 1^{1}S_0, \\
2^{++} & 1^{1}D_2, \\
1^{--} & 1^{3}S_1, \\
3^{--} & 1^{3}D_3.
\end{align*}
\]

In this two trajectories, the \( 0^{++} 1^{1}S_0 \) and the \( 1^{--} 1^{3}S_1 \) are confirmed states, while the \( 2^{++} 1^{1}D_2 \) and the
\[3^−− 1^3D_3 \text{ have not been fixed on. If } X(3872) \text{ is the } 2^+ 1^1D_2 \text{ state, the mass of the } 3^−− 1^3D_3 \text{ (M) can be derived in terms of the approximate parallelism relation}
\]
\[3.871^2 - 2.980^2 = M^2 - 3.097^2 \tag{5}\]

with \( M = 3.962 \text{ GeV}. \) In the meantime, the mass of the \( 2^−− 1^3D_2 \) can be obtained due to zero of hyperfine splitting of the \( 1D \) charmonium multiplet. The mass of the \( 2^−− 1^3D_2 \) (\( M_2 \)) is determined by

\[3.871 = \frac{3 \times 3.771 + 5M_2 + 7 \times 3.962}{15} \tag{6}\]

with \( M_2 = 3.804 \text{ GeV}, \) where the spin average is implied.

Therefore, the \( 1D \) multiplet is pitched down as follows

\[
\begin{align*}
1^3D_1 & \quad 1^3D_2 & \quad 1^1D_2 & \quad 1^3D_3 \\
3.771 & \quad 3.804 & \quad 3.871 & \quad 3.962 \text{ GeV}.
\end{align*}
\]

The mass of \( 1D \) spin triplets increases with the increase of \( J, \) and the whole mass sequence is reasonable. This analysis implies that the \( 2^−− 1^1D_2 \) charmonium arrangement of \( X(3872) \) is compatible with the ordinary mass relation in a multiplet. Furthermore, the analysis indicates that the \( 1^3D_2 \) is located around \( 3.804 \text{ GeV} \) and the \( 1^3D_3 \) is located around \( 3.962 \text{ GeV}. \)

The \( 2^− 1^1D_2 \) assignments of \( X(3872) \) could be analyzed in a similar way. In this case, two trajectories are consisted of

\[
\begin{align*}
0^+ & \quad 2^1S_0, & \quad 2^− & \quad 2^1D_2, \\
1^− & \quad 2^3S_1, & \quad 3^− & \quad 2^3D_3,
\end{align*}
\]

respectively. In this two trajectories, the \( 0^− 2^1S_0 \) and the \( 1^− 2^3S_1 \) are confirmed states, while the \( 2^+ 2^1D_2 \) and the \( 3^− 2^3D_3 \) have not been fixed on. If \( X(3872) \) is the \( 2^− 1^1D_2 \) state, the mass of \( 3^− 2^3D_3 \) (\( M \)) is determined by

\[M^2 - 3.686^2 = 3.871^2 - 3.638^2 \tag{7}\]

with \( M = 3.916 \text{ GeV}. \) Once the mass of the \( 3^− 2^3D_3 \) is known, the mass of the \( 2^− 2^3D_2 \) (\( M_1 \)) is obtained due to zero of hyperfine splitting of the \( 2D \) charmonium

\[3.871 = \frac{3 \times 4.153 + 5M_1 + 7 \times 3.916}{15} \tag{8}\]

with \( M_1 = 3.639 \text{ GeV}. \)

The \( 2D \) spectum are therefore determined as follows

\[
\begin{align*}
2^3D_1 & \quad 2^3D_2 & \quad 2^1D_2 & \quad 2^3D_3 \\
4.153 & \quad 3.639 & \quad 3.871 & \quad 3.916.
\end{align*}
\]

Obviously, the spectrum is exotic (\( M(2^3D_1) > M(2^3D_3) \)). That’s to say, the \( 2^+ 2^1D_2 \) charmonium arrangement of \( X(3872) \) seems impossible.

![Fig. 3: Existed trajectories on \((M^2, n)\)-plots for \(3^1S, 3^3P_2\) and \(3^1D_1\) charmonium.](image)

Now, let us study the parallelism of charmonium on \((M^2, n)\)-plots. From table.1, states in each group below construct a trajectory on \((M^2, n)\)-plots,

\[
\begin{align*}
1^3S_1 & \quad 3^1S_1 & \quad 3^3S_1 & \quad 3^1S_1, \\
1^3P_2 & \quad 3^3P_2, & \quad 3^3S_1 & \quad 4^3S_1, \\
1^3D_1 & \quad 3^3D_1 & \quad 3^1D_1, & \quad 3^3D_1,
\end{align*}
\]

respectively.

This three Regge trajectories on \((M^2, n)\)-plots is displayed in Fig.3. In the figure, the slope of line 1 is \( 3.259 \text{ GeV}^2 \), the slope of line 2 is \( 2.792 \text{ GeV}^2 \) and the slope of line 3 is \( 3.027 \text{ GeV}^2 \). It’s clear that the difference of the slopes to this three trajectories is small. These trajectories are approximately parallel. In terms of this approximate parallelism of Regge trajectories on \((M^2, n)\)-plots, some charmonium assignments to newly observed states could be examined.

As mentioned in the introduction, \( X(3872) \) may be the \( 1^{++} 2^3P_1 \) candidate. \( Y(3940) \) may be the \( 3^3P_0 \) or the \( 1^{++} 2^3P_0 \) candidate. If \( X(3872) \) is the \( 1^{++} 2^3P_1 \) and \( Y(3940) \) is the \( 0^{++} 2^3P_0 \), states in each group below will construct a trajectory on \((M^2, n)\)-plots:

\[
\begin{align*}
1^3S_1 & \quad 3^3S_1 & \quad 3^3S_1 & \quad 4^3S_1, \\
1^3P_2 & \quad 3^3P_2, & \quad 3^3P_1, & \quad 4^3P_1, \\
1^3D_1 & \quad 3^3D_1, & \quad 3^3D_1, & \quad 3^3D_1,
\end{align*}
\]

This five trajectories is plotted in Fig.4. If the assignments to these states are correct, five Regge trajectories
should be approximately parallel due to previous arguments.

The slope of line 1 is 3.259 GeV$^2$, the slope of line 2 is 2.792 GeV$^2$, the slope of line 3 is 3.027 GeV$^2$, the slope of line 4 is 2.665 GeV$^2$, and the slope of line 5 is 3.861 GeV$^2$. In this figure, it is easy to observe that the trajectory 5 (with Y(3940) involved) intersects with trajectories 2 and 4, while the trajectory 4 (with X(3872) involved) approximately parallels trajectories 1, 2 and 3. From these observations, it is reasonable to conclude that the $1^{++} 2S_1$ charmonium suggestion for X(3872) does not contradict with possible mass relations in charmonium. As a byproduct, the $2S_0$ charmonium assignment of Y(3940) seems impossible.

X(3872) may be a four-quark state ([cq][cq] tetraquark state or molecule state) [12, 22, 23, 24, 25, 26], but the four-quark state possibility of X(3872) will not be studied here. Four-quark states have been extensively studied for a long time [28, 29, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64, 65], unfortunately, their properties especially their dynamics and decay properties are still unfamiliar. So far, many states such as $f_0(600)$ (or $\sigma$), $f_0(980)$, $a_0(980)$, the unconfirmed $\kappa(800)$, $D_{sJ}^*(2317)^+$, $X(3872)$, $Y(4260)$, $X(1835)$ and $X(1812)$ have once been interpreted as four-quark state, but no one has been confirmed.

### IV. CONCLUSIONS AND DISCUSSIONS

The nature of X(3872) is still unclear. In addition to its $J^{PC}(1^{++}$ or $2^{++})$, whether it is a charmonium state or an exotic state is still uncertain. Instead of the production and decay properties, some mass relations of X(3872) are studied in the charmonium assignments. Through these relations and some phenomenological analyses, some assignments of X(3872) are examined.

If X(3872) is a $2^{++}$ state, it may be the $2^{++} 1^3D_2$ charmonium state while is unlikely to be the $2^{++} 1^3D_2$ charmonium state. If it is really the $2^{++} 1^3D_2$ charmonium state, the whole 1D multiplet is pitched down with the $1^3D_2$ located around 3.804 GeV and the $1^3D_3$ located around 3.962 GeV.

If X(3872) is a $1^{++}$ state, it may be the $1^{++} 2^3P_1$ charmonium. As a byproduct, it is found that Y(3940) is unlikely to be the $0^{++} 2^3P_0$ charmonium.

So far, the study of four-quark state and the study of meson near thresholds are not satisfactory. Four-quark state is usually invoked to explain the special decay properties of newly observed states, which in fact may be explained also without four-quark state [68]. Only when the properties of four-quark state are definitely clear, the four-quark state explanation of newly observed state will be satisfactory.

Of course, some properties in our analyses may not have firm foundation. The linearity and parallelism of Regge trajectories with neighborhood mesons stepped by 2 in J may be questionable (the deviations may be relevant to the spin-dependent interactions in quark models), however, the analyses here provide a complementary study of X(3872). These properties could be tested by more forthcoming experimental data and may give hints to the quark dynamics in hadron.

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