Regge-trajectory Analysis of $D^*_{SJ}(2317)^\pm$, $D_{SJ}(2460)^\pm$ and $D_{SJ}(2632)^+$ Mesons

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Status of investigations of the new observed strange mesons $D_{SJ}(2317)^\pm$, $D_{SJ}(2460)^\pm$ and $D_{SJ}(2632)^+$ is simply reviewed. A systemic classification to these states with Regge trajectories(RTs) was made. We found that $D_{SJ}(2317)^\pm$ and $D_{SJ}(2460)^\pm$ are reasonable to be arranged as $(0^+,1^+)$ states, but $D_{SJ}(2632)^+$ seems not possible to be an orbital excited tensor particle. As a byproduct, the non-strange charmed mesons including $D^*_c(2427)$ and $D^*(2637)^+$ were analyzed also.

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The problem of Quantum Chromodynamics(QCD) spectrum is a central issue in nonperturbative QCD and is connected to problems of confinement and mass generation, the flavor dependence of hadron spectrum and its connection to the type of potentials are still not clear. Charmed strange meson is an important system to study hadron spectrum for its internal heavy-light quark(anti-quark) components. There were limited experimental data for these mesons before, but the situation changes a lot since last year for the observation of several new states.

$D^*_{SJ}(2317)^\pm$ was first observed in $D^+_c\pi^-$ by BaBar[1], then confirmed by CLEO[2], BELLE[3] and FOCUS[4]. This state has mass 2317.4±0.9 MeV from PDG[5], about 40 MeV below $DK$ threshold, and has full width $\Gamma < 4.6$ MeV at 90% confidence level.

$D_{SJ}(2460)^\pm$ was first reported by CLEO[2] in $D^+_c\pi^0$ final states, and later observed by BELLE[6] and BaBar[5]. This state has mass 2459.3±1.3 MeV[5], about 50 MeV below $D^*K$ threshold, and has full width $\Gamma < 5.5$ MeV at 90% CL.

Very recently, a new surprisingly narrow charmed strange meson, $D_{SJ}(2632)^+$, was reported by SELEX[8], which correspond to $1S_0$ and $\bar{3}S_1$ states in normal quark models. The first excited states involving a P-wave excitation have light degrees of freedom of spin $j^P = \frac{1}{2}^+$ or $\frac{3}{2}^+$. The two doublets have $J^P = (0^+,1^+)$ and $J^P = (1^+,2^+)$, respectively.

When the spontaneous breaking of chiral symmetry was incorporated in, heavy light system could be studied in a chiral quark model[13]. In this model, the mesons are predicted to appear in parity-doubled bound states, which transform as linear representations of the light quark chiral symmetry. Parity doublet has the same mass splittings. For low lying mesons, the chiral partner of ground state $(0^-,1^-)$ is excited state $(0^+,1^+)$. The spectrum of corresponding excited D mesons have been calculated by W. Bardeen et al[14] recently. Their results are in good agreement with experimental data.

Calculations with other methods such as QCD string, unitarized meson model, MIT bag model and QCD sum rules[15] will not be introduced here.

Based on computations of the spectra and analyses to their decays, enormous discussions about the nature of these states have been triggered. $D^*_{SJ}(2317)^\pm$ was explained as $DK$ meson molecule and $D\pi$ atom[10], four quark state[17], P-wave $^3P_0\co$ $c\bar{s}$ mesons[14,15,18], baryonium[17] and mixed state[21]. $D_{SJ}(2460)^\pm$ has a similar explanation except for the P-wave $^3P_1\co$ $c\bar{s}$ explanation. $D_{SJ}(2632)^+$ was suggested to be a four quark state[21], tetraquarks[22] and the first radial excitation state of $D^*_S(2112)^{\pm,0}$. A systematic review to this excited subject could be found in [24].

So far, all the calculations of hadron spectrum have relied on some models. In this paper, we will make a phenomenological analysis to these excited states by means of approximate linear structure of the Regge trajectories and will make a systemic classification to them. In fact, if the new data about these resonances has been confirmed, it is possible to study the properties of their
Regge trajectories.

Several decades ago, it was known from meson phenomenology that the square of the hadron masses depend approximately linearly on the spin of the hadrons, which resulted in Regge trajectories theory. A Regge trajectory is a line in a $c$-Frautschi plot representing the spin of the lightest particles of that spin 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 state lying on corresponding trajectory. A Regge trajectory is approximately linear, while different trajectories are approximately parallel.

Based on much trial and experimentation, the flavor dependence of $q\bar{q}$ mesons was assumed to be on quark masses combination $m_1 + m_2$. A global description to Regge trajectories for all flavors was constructed\[26\]

$$\alpha(m_1 + m_2, t) = \alpha_I(m_1 + m_2, 0) + \alpha'(m_1 + m_2)t,$$

where the subscript $I$ refers to the leading trajectory.

When the mesons for which the lowest physical state is at $J = 1$ are concerned,

$$\alpha_I(m_1 + m_2, 0) = 0.57 - \frac{(m_1 + m_2)}{GeV},$$

$$\alpha'(m_1 + m_2) = \frac{0.9 \, GeV^{-2}}{[1 + 0.222(m_1 + m_2)^{3/2}]}.$$ 

For light quark mesons, $\alpha' \approx 0.9 \, GeV^{-2}$. For leading trajectories whose ground states begin at $J = 0$, they have an intercept approximately 0.5 MeV lower and follow a similar pattern.

For radial excited light $q\bar{q}$ mesons, trajectories on $(n, M^2)$-plots are obtained by\[27\]

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

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.

Properties of Regge trajectories of baryons\[28\], glueballs\[29\] and hybrids\[30\] have also been studied in many references.

Eq.\[2\] was constructed from a comprehensive phenomenological analysis of available experimental data for mesonic resonances of light, medium and heavy flavors. It has been supplemented by results from various phenomenological models.

As well known, a Regge trajectory may deviate from straight line, and different trajectories may deviate from parallelism\[31\]. The exact deviation depends on peculiar family of mesons, baryons, glueballs, hybrids and energy region. In fact, the non-linearity and non-parallelism of RT depends on intrinsic quark-gluon dynamics including flavor and $J$ dependence though the exact intrinsic dynamics is unknown. More detailed studies of Regge trajectories have been made in many more fundamental theories\[32\].

However, for mesons with small $J$, spin-orbit contribution is not significant, once the flavor dependence is the same, intrinsic dynamics is similar. Therefore the linearity and the parallelism of Regge trajectories are kept well. In the mean time, deviation from exchange degeneracy could not be large.

Based on these analyses and Eq. \[2\][3], the linearity, the parallelism and the masses combination $m_1 + m_2$ dependence(flavor dependence) of Regge trajectories for heavy light mesons with small $J$ are assumed in this paper. By means of these assumptions, we start our analysis to the spectrum of mesons.

In quark model, $q\bar{q}$ mesons could be marked by their quantum numbers, $I_n^{2S+1}L_J$. From PDG\[5\], we get Table I for charmed strange mesons. In this table, entries in the first volume are observed mesons, entries in the last volume are information from PDG, entries under $J^P$, $n^{2S+1}L_J$ and $J^P$ (light degrees of freedom) for those unconfirmed mesons are favored assignment by theoretical analyses.

In chiral quark model, the new observed $D_{SJ}^+(2317)^\pm$, $D_{SJ}(2460)^\pm$ are suggested to be $(0^+, 1^-)$ states, the chiral doubler of $(0^-, 1^-)$ states: $D_S(1969)^\pm$ and $D_S^*(2112)^\mp$. They have similar splitting $\approx 348 \, MeV$:

$$D_{SJ}(2460)^\pm - D_S^*(2112)^\mp \approx D_{SJ}^+(2317)^\pm - D_S(1969)^\pm.$$ (5)

Let us check this assignment with Regge trajectories. As well known, when the deviation from exchange degeneracy is not large, the $D_S^*(2112)^\mp (1^-)$ RT and the $D_{S2}(2573)^+(2^+)\ RT$ is almost the same and they determine a unique trajectory with slope

$$\alpha'(m_c + m_s) = \frac{1}{2.573^2 - 2.112^2} \, GeV^{-2} \approx 0.464 \, GeV^{-2}.$$ (6)

$D_S(1969)^\pm (0^-)$ and $D_{SJ}(2460)^\pm (1^+)$ determine another trajectory with slope

$$\alpha'(m_c + m_s) = \frac{1}{2.459^2 - 1.968^2} \, GeV^{-2} \approx 0.460 \, GeV^{-2}.$$ (7)

The slopes of two trajectories are approximately the same and two trajectories are parallel(a natural
of Eq. \[9\]. Our simple analysis supports the assignment for mesons: \(D_S(1969)^\pm (0^-), D_S(2112)^\pm (1^-), D_{SJ}(2460)^\pm (1^+)\) and \(D_{S2}(2573)^\pm (2^+)\), where the \(D_{SJ}(2632)^+\) lies outside the straight line. It is found that there exists no phenomenon called as spin-orbit inversion\[10, 33\], which may have relation with the dynamics spin-dependence of the confinement.

When the new reported \(D_{SJ}(2632)^+\) is assigned as the orbitally excited \(2^+ 3P_2\) state, \(D_S(2112)^\pm (1^-)\) and \(D_{SJ}(2632)^\pm (2^+)\) make a trajectory with slope

\[
\alpha'(m_c + m_s) = \frac{1}{2.632^2 - 2.112^2} \approx 0.405 GeV^{-2}
\]

The slope is much smaller than previous 0.460 GeV^{-2}. Obviously, if this assignment were right, deviation from parallelism of the two trajectories with the same flavor would be large. There is no masses dependence as Eq. \[9\] either. Therefore, once states \(D_S(1969)^\pm (0^-), D_S(2112)^\pm (1^-)\) and \(D_{SJ}(2460)^\pm (1^+)\) are confirmed by experiments, the assignment of \(D_{SJ}(2632)^+\) as a \(2^+ 3P_2\) tensor resonance seems impossible.

Now let us pay attention to the non-strange charmed mesons. Information of the observed non-strange charmed states are collected in Table II. The \(D^*(1969)^\pm (0^-), D^*(2112)^\pm (1^-)\) and \(D_{SJ}(2460)^\pm (1^+)\) make a trajectory with slope

\[
\alpha'(m_c + m_s) = \frac{1}{2.459^2 - 2.01^2} \approx 0.498 GeV^{-2}
\]

\(\alpha'(m_c + m_s, d)\) is bigger than \(\alpha'(m_c + m_s)\). It is obvious that the slopes of Regge trajectories decrease with increasing quark mass. The obtained result here about slopes supports the flavor dependence of Eq. \[9\].

\(D(1869)^\pm\) is the \(0^- 1^S_0\) state, but the \(1^- 1^P_1\) is missing! Recently, the new observed \(D^*_0(2308)^\pm\) and \(D^*_1(2427)^\pm\) were suggested as the \((0^+, 1^+)\) chiral doublet of \((0^-, 1^-)\) states: \(D(1869)^\pm\) and \(D^*(2010)^\pm\)\[24\]. If \(D^*_1(2427)^\pm\) were the missing \(1^- 1^P_1\) state, then \(D(1869)^\pm (0^-)\) and \(D^*_1(2427)(1^+)\) would make a trajectory with slope

\[
\alpha'(m_c + m_{u,d}) = \frac{1}{2.427^2 - 1.869^2} \approx 0.417 GeV^{-2}
\]

which is much smaller than previous 0.498 GeV^{-2}. Obviously, this assignment of \(D^*_1(2427)^\pm\) in inconsistent with the approximate linearity, the parallelism and the flavor dependence of Regge trajectories. From the linearity, the parallelism and the flavor dependence of Regge trajectories, the missing \(1^- 1^P_1\) state should have mass \(\approx 2350\) MeV.

Similar to \(D_{SJ}(2632)^+\), the recently observed \(D^*(2637)^+\) by DELPHI in the \(D^* \pi\) channel\[37\] seems impossible to be assigned as a tensor state. The Chew-Frautschi plots for these mesons were drawn in Fig. 2.

From the final states in its decay, \(D_{SJ}(2632)^+\) must have \(J^P = 0^+, 1^-, 2^+\) . . . . . . . So this state has been suggested\[22\] as the first radial excited state of \(D_S(2112)^\pm (1^-)\). \(D^*(2637)^+\) was suggested as the first radial excited states of \(D^*(2010)^\pm (1^-)\)\[33\]. If \(D^*(2637)^+\),

\[
\begin{array}{cccc}
\text{States} & J^P & n^{2S+1}L_J & J^p & \text{PDG note} \\
D(1869)^\pm & 0^- & 1^S_0 & & \\
D^*(2010)^\pm & 1^- & 1^P_1 & & \\
D^*_0(2308)^\pm & 0^+ & 1^P_0 & \frac{1}{2}^+ & ? \\
D^*_1(2427)^\pm & 1^+ & 1^P_1 & \frac{1}{2}^- & ? \\
D^*_1(2420)^0 & 1^+ & 3^P_1 & \frac{1}{2}^- & J, P\ need\ confirmation \\
D^*_2(2460)^\pm & 2^+ & 3^P_2 & \frac{3}{2}^+ & J^P = 2^+\ strongly\ favored \\
D^*(2637)^+ & 1^- & 2^S_1 & & \\
\end{array}
\]

TABLE II: Spectrum of Non-strange Charmed Mesons.
$D_{sJ}(2632)^+$ are really the first radial excited states of $D^*(2100)^\pm (1^-)$, $D^*_s(2112)^\pm (1^-)$, their spectra are exotic: $1^- 3S_1$ non-strange charmed meson lies below corresponding charmed strange meson, but the first radial excited non-strange charmed state lies above corresponding charmed strange meson. Furthermore, their trajectories on $(n, M^2)$-plots are not consistent with Eq. 4 for light mesons.

In conclusion, some interesting results on the charmed strange and non-strange mesons have been obtained:

1. The slopes of the Regge trajectories decrease with increasing quark mass, which is consistent with Eq. 3.
2. The assignment of $D_{sJ}(2460)^\pm$ as $1^- 1P_1$ state is reasonable while the assignment of $D'_s(2427)$ as $1^- 1P_1$ state seems impossible. The mass of the right candidate of $1^- 1P_1$ non-strange charmed state is predicted to have mass $\approx 2350$ MeV.
3. The assignment of $D_{sJ}(2632)^+$ and $D^*(2637)^+$ as the $2^+ 3P_2$ state seems impossible.
4. If $D^*(2637)^+$, $D_{sJ}(2632)^+$ are really the first radial excited states, their spectra are exotic and their Regge behavior is different from corresponding one for light mesons.

However, when we turn back to look at the entries in Table II and III, we find that we still have little knowledge to heavy light charmed mesons. Quantum numbers of some states are required to be measured, or to be confirmed. Some predicted states should be searched for, and more decays modes should be detected. We hope the investigation here will be useful to further experiments.

The linearity, the parallelism and the flavor dependence of Regge trajectories have been assumed in our analysis, these properties for other mesons and possible deviations (and their origin) deserve more study. If the approximate linearity, parallelism and the flavor dependence of Regge trajectories of charmed mesons are confirmed when more experimental data are accumulated, more hints about mesons’ intrinsic flavor dependence of their spectrum and about the type of confinement potential for heavy light systems would be discerned. Furthermore, reasonable conclusions from Regge phenomenology are hoped to be incorporated into the study of quark models.

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