\[ D_{sJ}^*(2317)^+ : \text{a } P \text{ state from the light cone harmonic oscillator model?} \]

Shan-Gui Zhou\(^1,2,3,4,\) and Hans-Christian Pauli\(^1,\dagger\)

\(^1\)Max-Planck-Institut für Kernphysik, 69029 Heidelberg, Germany
\(^2\)School of Physics, Peking University, Beijing 100871, China
\(^3\)Institute of Theoretical Physics, Chinese Academy of Sciences, Beijing 100080, China
\(^4\)Center of Theoretical Nuclear Physics, National Laboratory of Heavy Ion Accelerator, Lanzhou 730000, China

(Dated: May 9, 2003)

We show that the mass of the recently found meson, \( D_{sJ}^*(2317)^+ \) could be reproduced by an effective light cone Hamiltonian model with a harmonic oscillator potential as confinement — the light cone harmonic oscillator model.

PACS numbers: 14.40.Lb, 11.10.Ef, 12.39.-x

A recent experiment by the BABAR collaboration observes a new narrow \( c\bar{s} \) state, \( D_{sJ}^*(2317)^+ \) with the invariant mass \( M = 2.32 \text{ GeV}/c^2 \) \([1]\). The state has natural spin-parity and the low mass suggests a \( J^P = 0^+ \) assignment. In the convention of the quark model (QM), correspondingly, \( L = 1, S = 1 \) and \( J = 0 \), i.e., \( 2S+1L_J = 3P_0 \). However, as argued in Ref. \([1]\), both the small mass and the small width are in conflict with most model predictions available then \([2, 3, 4]\). For example, the mass of this state is typically predicted between 2.4 and 2.6 GeV/c\(^2\) in Refs. \([2, 3, 4]\) (cf. Table I). Due to these conflicts, it is suggested in Ref. \([1]\) either to modify those models or to attribute this state, e.g., as a four quark state. But we show here that \( D_{sJ}^*(2317)^+ \) is still consistent with the normal picture. The mass of \( D_{sJ}^*(2317)^+ \) could be reproduced by an effective light cone Hamiltonian model with a harmonic oscillator potential as confinement — the light cone harmonic oscillator (LCH) model without changing the parameters fixed previously.

The LCH model, a light-cone QCD-inspired model, with the mass squared operator consisting of a harmonic oscillator potential as confinement — the light cone harmonic oscillator model (LCH).

For the present purpose, the model Hamiltonian reads,

\[ M_{ho}^2 \varphi(\vec{r}) = M^2 \varphi(\vec{r}). \tag{1} \]

Compared to Refs. \([5, 6]\), the Dirac-delta interaction is omitted here because it only acts on \( S \) states. But we add a phenomenological spin-orbit term with the strength \( \kappa \) being a free parameter to be determined by the data (For the results with a more reasonable spin-orbit term, see Ref. \([7]\)). The mass squared operator is then

\[ M_{ho}^2 = 2m_s \left( -\frac{\nabla^2}{2m_r} + \frac{1}{2}m_s + v(r) + \kappa \vec{L} \cdot \vec{S} \right), \tag{2} \]

in units of \( \hbar = c = 1 \). \( m_s \) and \( m_r \) are the sum and the reduced mass of the two quarks with constituent quark masses \( m_1 \) and \( m_2 \). The masses for the strange and charm quarks were determined in Ref. \([5, 6]\) as 0.478 and 1.749 GeV, respectively.

\[ E_{LS} = \begin{cases} +\kappa L, & \text{for } J = L + 1, \\ -\kappa, & \text{for } J = L, \\ -\kappa(L + 1), & \text{for } J = L - 1. \end{cases} \tag{5} \]

The mass of the singlet state \( D_s(1P_1) \), which is independent of \( \kappa \), is calculated from Eq. (4) as 2.494 GeV. It deviates from the experimental value \( M(D_{s1}(2536)^+) \)

\[ \begin{array}{cccccc}
\text{\( n^S \)} & \text{\( L \)} & \text{\( n^S \)} & \text{\( L \)} & \text{Data} & \text{Ref. [3]} & \text{Ref. [4]} & \text{This work} \\
0^1P_0 & 0^1P_0 & 2.537 & 2.53 & 2.535 & 2.494 & 2.494 & 2.494 \\
0^1P_1 & 0^1P_1 & 2.573 & 2.59 & 2.581 & 2.573 & 2.573 & 2.573 \\
0^3P_0 & 0^3P_0 & 2.32 & 2.48 & 2.487 & 2.328 & 2.328 & 2.328 \\
0^3P_1 & 0^3P_1 & 2.536 & 2.55 & 2.535 & 2.494 & 2.494 & 2.494 \\
0^5P_0 & 0^5P_0 & 2.53 & 2.55 & 2.535 & 2.573 & 2.573 & 2.573 \\
0^5P_1 & 0^5P_1 & 2.55 & 2.605 & 2.605 & 2.412 & 2.412 & 2.412 \\
\end{array} \]

\[ \begin{array}{cccccc}
\text{\( n^S \)} & \text{\( L \)} & \text{\( n^S \)} & \text{\( L \)} & \text{Data} & \text{Ref. [3]} & \text{Ref. [4]} & \text{This work} \\
0^1P_0 & 0^1P_0 & 2.537 & 2.53 & 2.535 & 2.494 & 2.494 & 2.494 \\
0^1P_1 & 0^1P_1 & 2.573 & 2.59 & 2.581 & 2.573 & 2.573 & 2.573 \\
0^3P_0 & 0^3P_0 & 2.32 & 2.48 & 2.487 & 2.328 & 2.328 & 2.328 \\
0^3P_1 & 0^3P_1 & 2.536 & 2.55 & 2.535 & 2.494 & 2.494 & 2.494 \\
0^5P_0 & 0^5P_0 & 2.53 & 2.55 & 2.535 & 2.573 & 2.573 & 2.573 \\
0^5P_1 & 0^5P_1 & 2.55 & 2.605 & 2.605 & 2.412 & 2.412 & 2.412 \\
\end{array} \]
2.536 GeV [8] by only \( \sim 0.04 \) GeV. The agreement is reasonable considering that the mixing between the singlet and the triplet \( J = 1 \) states is not included in this simple model. For the same reason, we will use the theoretical mass of \( D_s(1P_1) \) and the data of \( 3P_2, D_s^*(2573)^+ \) to determine the parameter \( \kappa \),

\[
\kappa = \frac{1}{2m_s} \left[ M^2(3P_2) - M^2(1P_1) \right] = 0.0899 \text{ GeV},
\]

where \( m_s \) is the summation of the strange and charm quark masses. The masses of the other two triplet \( P \) states, \( 3P_1 \) and \( 3P_0 \) are easily calculated from Eqs. (4) and (5) and given in Table I where predictions from Refs. [3, 4] are also included for comparison. The present prediction for the mass of the lowest \( P \) state is very close to the data. This implies that \( D_s^*(2317)^+ \) might still be a “normal” meson consisting of two constituent quarks.

From the LCH model, the four \( P \) states are equally spacing in mass squared as seen from Eqs. (4) and (5) and Table I. Apparently this is not the case in the experiment. As mentioned before, one of the reasons might be that there is an admixture between \( 1P_1 \) and \( 3P_1 \) because only the total angular momentum \( \vec{J} = \vec{L} + \vec{S} \) should be conserved. This coupling is not included in the simple LCH model.

There are many other phenomenological scenarios for the spin-orbit splitting in hadron spectroscopy, see e.g. Ref. [9]. Inclusion of those scenarios would improve the prediction power of our model but would also bring out more complication. We therefore leave that for a future task.

In summary, the \( P \) states of the charmed strange meson are investigated by using an effective light cone Hamiltonian model with a harmonic oscillator potential. We conclude that \( D_s^*(2317)^+ \) can still be consistent with the normal picture of mesons. The investigation of other \( L \neq 0 \) states in all \( q\bar{q} \) sectors is in progress.

We thank Harun Omer for drawing our attention to Ref. [1]. S. G. Z. was partly supported by the Major State Basic Research Development Program of China Under Contract Number G2000077407.

\* Electronic address: sgzhou@mpi-hd.mpg.de
† Electronic address: pauli@mpi-hd.mpg.de

[1] BABAR Collaboration: B. Aubert, et al., Phys. Rev. Lett. 90, 242001 (2003), [arXiv: hep-ex/0304021 (2003)].
[2] S. Godfrey and N. Isgur, Phys. Rev. D 32, 189 (1985).
[3] S. Godfrey and R. Kokoski, Phys. Rev. D 43, 1679 (1991).
[4] M. Di Pierro and E. Eichten, Phys. Rev. D 64, 114004 (2001).
[5] T. Frederico, H. C. Pauli, and S. G. Zhou, Phys. Rev. D 66, 054007 (2002).
[6] T. Frederico, H. C. Pauli, and S. G. Zhou, Phys. Rev. D 66, 116011 (2002).
[7] S. G. Zhou, contribution to “Light Cone Workshop 2003, Durham” proceedings, [arXiv: hep-ph/0310362].
[8] K. Hagiwara et. al., Phys. Rev. D 66, 010001 (2002).
[9] D. Flamm and F. Schöberl, Introduction to the Quark Model of Elementary Particles, Vol. I, Chap. 4, Gordon and Breach, Science Publishers, Inc. (1982).