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WHAT ARE THE $X(3872)$ AND D_{sJ} PARTICLES?

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ABSTRACT

Recently, three new states, provisionally named $D^*_{sJ}(2317)^+$, $D_{sJ}(2460)^+$, and $X(3872)$, were discovered by BaBar, CLEO, and Belle, respectively. None of the new states is readily accommodated by existing models of meson spectroscopy. While the two D_{sJ} states are suggestive of the hitherto-unobserved P-wave $c\bar{s}$ doublet, this interpretation may require modification of standard interquark-potential models. The $X(3872)$ may be a $D^0\bar{D}^{*0}$ molecule, an excited $c\bar{c}$ state, or a hybrid $c\bar{c}g$ state. This paper surveys the experimental evidence and considers various theoretical explanations for these novel states.

1 Introduction

The past year has seen the discovery of three new particles that challenge the current understanding of meson spectroscopy. First, the BaBar collaboration observed a narrow resonance near 2.32 GeV in the $D_s^+\pi^0$ spectrum [1]. Shortly thereafter, the CLEO Collaboration announced the observation of a similarly narrow resonance near 2.46 GeV in the $D_s^{*+}\pi^0$ spectrum [2]. The intrinsic widths of the two states were measured by CLEO to be smaller than 7 MeV at 90% C.L. Although these new states have been named $D_{sJ}^*(2317)^+$ and $D_{sJ}(2460)^+$ and interpreted as the missing P-wave doublet of the $c\bar{s}$ system, their masses are significantly lower than theoretical predictions.

Not long after these discoveries, the Belle Collaboration reported the observation of a 3.872-GeV $J/\psi\pi^+\pi^-$ resonance in the exclusive decay $B^+ \to K^+J/\psi\pi^+\pi^-$ [3]. The signal, which was measured to have an intrinsic width smaller than 2.3 MeV at 90% C.L., had a statistical significance greater than 10σ and could not be reproduced in generic Monte Carlo. While this state, provisionally named the $X(3872)$, may be charmonium, it does not exhibit the theoretically predicted properties of any of the missing $c\bar{c}$ states.

The following sections will briefly review the spectroscopy of the $c\bar{s}$ and $c\bar{c}$ systems, survey the experimental evidence, and outline the difficulties in reconciling the observations with theory.

2 The $D_{sJ}^*(2317)^+$ and $D_{sJ}(2460)^+$ Particles

2.1 The $c\bar{s}$ System

Two different approaches can be used to predict the properties of P-wave charmed mesons [4]. The first is a non-relativistic quark model with an interquark potential that is partly Coulombic. In the limit where the mass of one of the quarks approaches infinity, the light-quark angular momentum $\mathbf{j}_l = \mathbf{s}_l + \mathbf{l}$ is conserved, and the P-wave states are split into two levels, with $j_l = 3/2$ and $1/2$. Since the heavy quark in a real meson is not infinitely massive, its spin cannot be neglected completely. The conserved quantity thus becomes the total angular momentum $\mathbf{J} = \mathbf{j}_l + \mathbf{s}_h$, and the levels are split further, the $j_l = 3/2$ into $J = 2$ and $J = 1$, and the $j_l = 1/2$ into $J = 1$ and $J = 0$. Since j_l is only approximately conserved, the two states with $J = 1$ can mix. The S-wave and P-wave states for the $c\bar{s}$ system are shown in Fig. 1.

The second approach employs heavy-quark effective theory (HQET) [6]. In the limit where the mass of the heavy quark approaches infinity, the spin of the heavy quark and the angular momentum of the light quark are separately

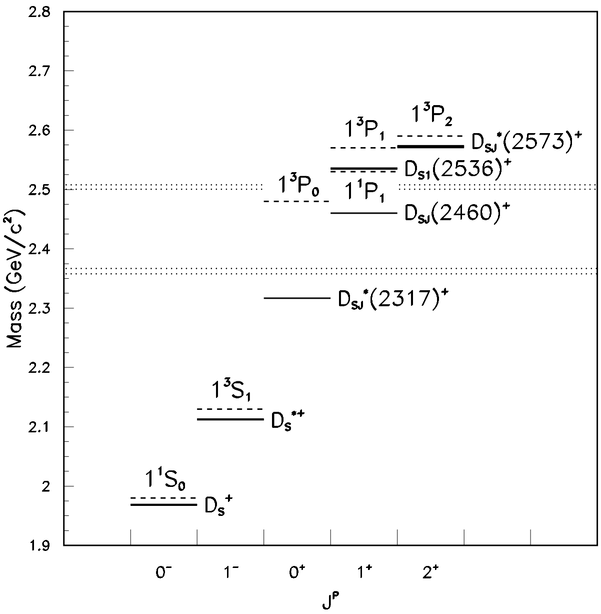

Figure 1: *The S-wave and P-wave states of the $c\bar{s}$ system. Dashed lines indicate the theoretical predictions of Godfrey and Isgur [5], and solid lines indicate the measured values. The dotted lines mark, from top to bottom, the $D^{*+}K^0$, $D^{*0}K^+$, D^+K^0, and D^0K^+ thresholds. The spectroscopic notation used is $n^{2s+1}L_J$, where n is the principal quantum number, s is the total spin, L is the orbital angular momentum, and J is the total angular momentum. Note that since s is not a good quantum number, the 1^3P_1 and 1^1P_1 states can mix.*

conserved by the strong interaction. This heavy-quark symmetry (HQS) is approximately true in the case of a heavy quark of finite mass and greatly simplifies QCD calculations.

These theoretical considerations have met with reasonable success in predicting the properties of the S-wave and P-wave $j_l = 3/2$ states of the $c\bar{s}$ system [4]. The P-wave $j_l = 1/2$ states were expected to be broad and to decay strongly to isospin-conserving DK and D^*K final states. The observation of two narrow states decaying to $D_s^+\pi^0$ and $D_s^{*+}\pi^0$ is therefore surprising. As Fig. 1 indicates, however, if the observed states are indeed the $j_l = 1/2$ doublet, their unexpectedly low masses guarantee their small widths by closing the strong-decay channels. The masses of the new states are significantly below potential-model expectations [5, 7] and are nearly the same as their $c\bar{u}$ counterparts recently observed by Belle [8].

2.2 Experimental Details

Following the initial observations by BaBar and CLEO, BaBar confirmed the $D_{sJ}(2460)^+$ result of CLEO [9], and Belle reconstructed both particles in exclusive decays of the type $B \to \bar{D}D_{sJ}$ [10]. Belle further observed the $D_{sJ}(2460)^+$ in its $D_s^+\gamma$ and $D_s^+\pi^+\pi^-$ final states. The masses measured for $D_{sJ}^*(2317)^+$ and $D_{sJ}(2460)^+$ by the three groups are listed in Table 1.

Table 1: *The D_{sJ} masses as measured by BaBar, Belle, and CLEO. Here and throughout, whenever two errors are quoted for a measurement, the first is statistical and the second systematic.*

	$D_{sJ}^*(2317)^+$	$D_{sJ}(2460)^+$
BaBar	$2317.3 \pm 0.4 \pm 0.8$ MeV/c^2	$2458.0 \pm 1.0 \pm 1.0$ MeV/c^2
Belle	$2317.2 \pm 0.5 \pm 0.9$ MeV/c^2	$2456.5 \pm 1.3 \pm 1.3$ MeV/c^2
CLEO	$2318.5 \pm 1.2 \pm 1.1$ MeV/c^2	$2463.1 \pm 1.7 \pm 1.2$ MeV/c^2

For the decays $D_{sJ}^*(2317)^+ \to D_s^+\pi^0$ and $D_{sJ}(2460)^+ \to D_s^{*+}\pi^0$ to conserve parity, the spin-parity of $D_{sJ}^*(2317)^+$ must be natural (i.e. $J^P = 0^+, 1^-, 2^+, \ldots$) and $D_{sJ}(2460)^+$ unnatural (i.e. $J^P = 0^-, 1^+, 2^-, \ldots$). The narrow width of the $D_{sJ}(2460)^+$ in spite of its mass above DK threshold is consistent with an unnatural J^P assignment. The observation of $D_{sJ}(2460)^+ \to D_s^+\gamma$ excludes $J = 0$ for $D_{sJ}(2460)^+$, and Belle's angular analysis of this decay further rules out $J = 2$ while being consistent with $J = 1$. The decay $D_{sJ}(2460)^+ \to D_s^+\pi^+\pi^-$ strengthens these conclusions by eliminating $J^P = 0^+$.

If the interpretation of the new particles as the $j_l = 1/2$ doublet of the $c\bar{s}$ system is correct, certain decay modes that violate parity and angular-momentum conservation should not be seen. Table 2 shows several allowed and forbidden final states, along with measured branching ratios or upper limits.

Setting aside the low masses, the experimental evidence is entirely consistent with the interpretation of the new particles as the $j_l = 1/2$ doublet of the P-wave $c\bar{s}$ system.

Table 2: *Measured branching ratios and upper limits at 90% C.L. for various possible* $D^*_{sJ}(2317)^+$ *and* $D_{sJ}(2460)^+$ *final states. Whether a given decay is allowed(A) or forbidden(F) by parity and angular-momentum conservation is also indicated. Values are given as a fraction of the branching ratio to* $D_s^+\pi$ *and* $D_s^{*+}\pi^0$ *for* $D^*_{sJ}(2317)^+$ *and* $D_{sJ}(2460)^+$*, respectively.*

Decay Mode	$D^*_{sJ}(2317)^+$		$D_{sJ}(2460)^+$	
$D_s^+\pi^0$	A	$\equiv 1.000$	F	Belle: ≤ 0.21
$D_s^{*+}\pi^0$	F	CLEO: < 0.11	A	$\equiv 1.000$
$D_s^+\gamma$	F	BaBar: not observed CLEO: < 0.052 Belle: ≤ 0.05	A	CLEO: < 0.49 Belle: $0.55 \pm 0.13 \pm 0.08$
$D_s^{*+}\gamma$	A	BaBar: not observed CLEO: < 0.059 Belle: ≤ 0.18	A	CLEO: < 0.16 Belle: ≤ 0.31
$D_s^+\pi^+\pi^-$	F	CLEO: < 0.019 Belle: ≤ 0.004	A	CLEO < 0.08 Belle: $0.14 \pm 0.04 \pm 0.02$
$D_s^+\gamma\gamma$	A	BaBar: not observed	A	–
$D^*_{sJ}(2317)^+\gamma$	–	–	A	CLEO: < 0.58

2.3 Theoretical Interpretations

Numerous theories have been proposed to explain the low masses of the new particles. These include attempts to improve standard HQET or quark-model arguments [11], as well as more exotic proposals such as a DK meson molecule, a $D\pi$ atom, or a $cq\bar{q}\bar{q}$ state [12]. One possible explanation may be that the $c\bar{s}$ mass spectrum is distorted as a result of coupling to the $D^{(*)}_{(s)}K$ threshold [13]. Searching for radiative decays may help distinguish between $c\bar{s}$ and DK-molecule interpretations. [14]. Since the low masses may be symptomatic of a serious inadequacy of the current theory, it is important that more work be done to further specify the properties of the new particles.

3 The $X(3872)$ Particle

3.1 The $c\bar{c}$ System

The decay of the $X(3872)$ to $J/\psi\pi^+\pi^-$ suggests that it may be a $c\bar{c}$ state. As the spectrum in Fig. 2 indicates, there are numerous $c\bar{c}$ states that have not yet been observed. In particular, the $h_c(1^1P_1)$, $\eta_{c2}(1^1D_2)$, and $\psi_2(1^3D_2)$ are expected to lie below $D\bar{D}^*$ threshold and thus be narrow.

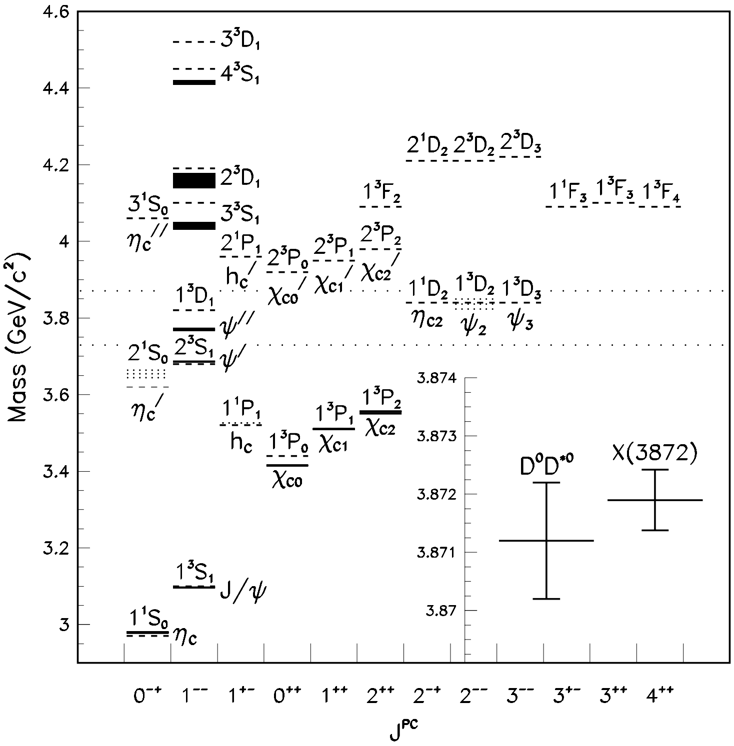

Figure 2: *The $c\bar{c}$ spectrum. Dashed lines indicate the theoretical predictions of Godfrey and Isgur* [5]*, and solid lines indicate measured values according to the PDG* [15]*. Measurements that need confirmation are indicated by dotted lines. The two dotted lines across the plot mark the $D^0\bar{D}^0$ and $D^0\bar{D}^{*0}$ thresholds. The inset compares the $X(3872)$ mass (obtained by adding the statistical and systematic errors of each experiment in quadrature and calculating a weighted average of the four experiments) to the $D^0\bar{D}^{*0}$ threshold. The spectroscopic notation is the same as that of Fig. 1.*

3.2 Experimental Details

Belle's observation of the $X(3872)$ has been confirmed by CDF [16], DØ [17], and BaBar [18]. The masses measured are shown in Table 3.

Table 3: *The $X(3872)$ masses measured by BaBar, Belle, CDF II, and DØ.*

	$X(3872)$
Belle	$3872.0 \pm 0.6 \pm 0.5$ MeV$/c^2$
CDF	$3871.3 \pm 0.7 \pm 0.4$ MeV$/c^2$
DØ	$3871.8 \pm 3.1 \pm 3.0$ MeV$/c^2$
BaBar	3873.4 ± 1.4 MeV$/c^2$

The narrow width of the $X(3872)$ despite its mass above $D\bar{D}$ threshold suggests that its decay to $D\bar{D}$ may be forbidden. Assuming that this is the case, all $c\bar{c}$ states with small J and natural J^P may be ruled out [19]. If known particles as well as states with predicted masses significantly different from that of the $X(3872)$ are also excluded, six possibilities remain: $\eta_c''(3^1S_0)$, $\chi_{c1}'(2^3P_1)$, $\eta_{c2}(1^1D_2)$, $h_c'(2^1P_1)$, $\psi_2(1^3D_2)$, and $\psi_3(1^3D_3)$.

The first three of these states have even C-parity, while the remaining three have odd C-parity. A measurement of the C-parity of the $X(3872)$ can thus be used to further reduce the number of possibilities. If the $X(3872)$ is a $c\bar{c}$ state with even (odd) C-parity, then $X(3872) \to J/\psi\rho^0$ should be allowed (forbidden), and $X(3872) \to J/\psi\pi^0\pi^0$ should be forbidden (allowed). The relative branching ratios of the $X(3872)$ to $J/\psi\pi^+\pi^-$ and $J/\psi\pi^0\pi^0$ can also distinguish between a $c\bar{c}$ state and something more exotic [20, 21]. Belle has noted that the $\pi^+\pi^-$ invariant-mass distribution tends to peak near the kinematic boundary, which is near the ρ^0 mass. This suggests that the pion pair may come from a ρ^0, although a similar tendency to crowd the kinematic boundary is also seen in the dipion mass distribution of $\psi' \to J/\psi\pi^+\pi^-$. The observation is far from conclusive, and further study is required.

The $\psi_2(1^3D_2)$ may be easy to observe at B-factories via its $J/\psi\pi^+\pi^-$ final state [22]. If the $X(3872)$ is the $\psi_2(1^3D_2)$, however, its branching ratio to $\chi_{c1}\gamma$ should be several times greater than its branching ratio to $J/\psi\pi^+\pi^-$ [23]. Belle has placed an upper limit on the ratio of partial widths to $\chi_{c1}\gamma$ and $J/\psi\pi^+\pi^-$ of 0.89 at 90% C.L. [3]. Similarly, the $\psi_3(1^3D_3)$ is expected to have an appreciable branching ratio to $\chi_{c2}\gamma$ [20]. Belle has placed an upper limit on the ratio of partial widths to $\chi_{c2}\gamma$ and $J/\psi\pi^+\pi^-$ of 1.1 at 90% C.L. [24].

The $\eta_c''(3^1S_0)$ appears too large in mass and width to be the $X(3872)$. The $\eta_{c2}(1^1D_2)$, $\chi_{c1}'(2^3P_1)$ and $h_c'(2^1P_1)$ are not expected to have significant branching fractions to $J/\psi\pi^+\pi^-$ [20]. The $h_c'(2^1P_1)$ is also ruled out by Belle's angular analysis of $B^+ \to K^+ J/\psi\pi^+\pi^-$, the results of which are inconsistent with a J^{PC} assignment of 1^{+-} [24].

These considerations are far from conclusive; in particular, coupling to open-charm channels can distort potential-model predictions for states above charm threshold [25]. Nevertheless, there appears to be no obvious $c\bar{c}$ candidate for the $X(3872)$.

3.3 Theoretical Interpretations

One striking coincidence is the overlap between the mass of the $X(3872)$ and the D^0D^{*0} threshold (see Fig. 2). This mass degeneracy has led to speculation that the $X(3872)$ may be a lightly-bound $D^0\bar{D}^{*0}$ molecule [20, 21, 26]. Such meson molecules were predicted as early as the 1970s [27].

It is also possible that the $X(3872)$ is a $c\bar{c}g$ hybrid state [28, 29]. Such a state would be expected to have a narrow width and a large branching ratio to $J/\psi\pi^+\pi^-$, but a mass higher than 4 GeV.

4 Conclusion

The observation of the $D_{sJ}^*(2317)^+$, $D_{sJ}(2460)^+$, and $X(3872)$ have challenged the predictivity of current models of meson spectroscopy. While these new states may require no more than minor alterations to the theory, they may also be exotic particles that will lead to new breakthroughs in meson spectroscopy. Further experimental results on all three states will be important in resolving the situation.

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