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Spectroscopy of the excited D_s^+ mesons

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Summary. — The discoveries of the $D_{s0}^*(2317)^+$ and $D_{s1}(2460)^+$ mesons challenge our understanding of quantum chromodynamics. After almost 20 years, the nature of these hadrons is still subject of debate and many models have been proposed to explain their unexpected masses: standard charmed-strange mesons, DK molecules and tetraquarks. The LHCb experiment has studied the production of excited D_s^+ meson in prompt proton-proton collisions and from b-hadron decays. Precise measurement of their properties and observation of new D_s^+ states have been reported. The latest results on the spectroscopy of the charmed-strange mesons and the prospect to investigate their nature will be presented.

1. – Charmed spectroscopy at LHCb

A meson is a composite particle of an even number of quarks (q) and antiquarks ($\bar{q}$), bound together by strong interactions. In 1964, Gell-Mann and Zweig [1] described mesons, for the first time, as combinations of $q\bar{q}$ pairs of quarks u, d and s, with a model that was subsequently extended to all existing quarks: u, d, c, s, t, b. The first observed meson was the pion π, a state predicted by Yukawa [2] to explain the strong force between nucleons in nuclei. Later on, mesons with a charm c quark, the D^0 ($c\bar{u}$) and D^+ ($c\bar{d}$) states [3, 4], were observed in 1976, followed by the discovery of the D_s^+ ($c\bar{s}$) meson in 1983 [5]. The expected and observed D_s^+ excited states are shown in fig. 1 according to their quantum numbers.

The LHCb experiment has largely contributed to the D_s^+ spectroscopy [6] by exploiting its high detection performance [7] and a large D_s^+ production cross-section at LHC equal to $\sigma(pp \to D_s^+ X) = 353 \pm 9 \pm 76 \mu b$ [8]. Notably, the LHCb collaboration has reported the $D_{s3}^*(2860)$ resonance, the first spin-3 meson ever observed in the B-meson production. In particular, the $D_{s1}^*(2860)$ and $D_{s3}^*(2860)$ resonances have been distinguished in a broad structure at $2.86\,\text{GeV}/c^2$ by fitting the Dalitz plot of exclusive

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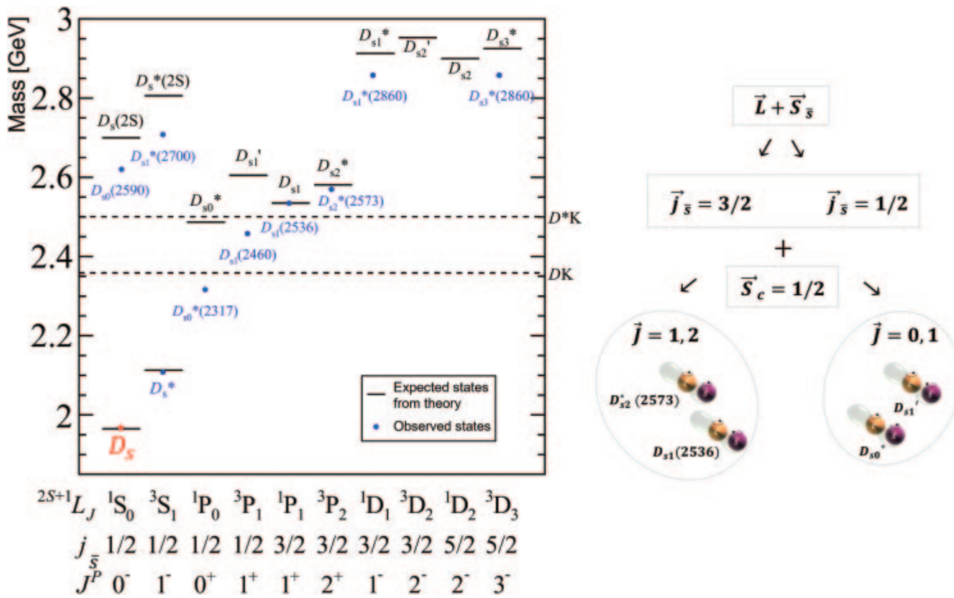

Fig. 1. – Left: spectrum of the excited D_s^+ mesons. The classification is based on masses and quantum numbers. L is the orbital angular momentum between constituent quarks (S, P, D correspond to $L = 0, 1, 2$ respectively); $S = 0, 1$ is the sum of quark spins and J is the total spin of meson; P is the parity. Right: excited P-wave states ($\vec{L} = 1$) in the heavy quark limit model.

three-body decays $B_s^0 \to \overline{D}^0 K^- \pi^+$ [9,10]. Another remarkable result is the recent observation of the new state $D_{s0}(2590)^+$ [11], which is interpreted as the radially excitation of the D_s^+ ground state (fig. 1).

2. – The puzzle of the $D_{s1}(2460)^+$ state in the heavy quark limit model

In the heavy quark limit model [12,13], D_s^+ states with one heavy quark c are modelled as hydrogen atoms with the heavy nucleus corresponding to the c quark and the electron around the nucleus corresponding to the lighter $\bar{s}$ quark. In such model, the bounding energy depends on spin-orbit coupling of the light $\bar{s}$ quark only. The heavy quark limit model is able to predict the existence of D_s^+ excited states, according to the sums rules of the quarks orbital momentum and spin. In fig. 1, the excited P-wave states ($L = 1$) prediction scheme is shown: after the spin-orbit coupling is made, involving only the spin $\vec{S}_{\bar{s}} = 1/2$ of the light quark, the total angular momentum of that quark is $\vec{j}_{\bar{s}} = \vec{L} + \vec{S}_{\bar{s}}$ that can be equal to 1/2 or 3/2. Then the spin of the meson is obtained summing $\vec{j}_{\bar{s}}$ to the spin $\vec{S}_c = 1/2$ of the heavier quark. Four new possible states emerge: the resonances D^*_{s0} and D'_{s1} with spin-parity 0^+ and 1^+, and the resonances $D_{s1}(2536)$ and $D^*_{s2}(2573)$ with spin parity 1^+ and 2^+ respectively. While the latter two states have been observed, thus confirmed, by studying the DK and D^*K mass spectra [14,15], it is not clear yet if the first two states, featured by $\vec{j}_{\bar{s}} = 1/2$ quantum number, have been observed. Indeed, the theory predicted them as broad states with masses large enough so that the dominant decays would have been the DK and/or D^*K final states. However, two narrow resonances, named $D^*_{s0}(2317)^+$ and $D_{s1}(2460)^+$, were observed by the

BABAR [16] and the *CLEO* [17] Collaborations, having mass smaller than all theoretical predictions and decaying to the isospin-violating $D_s^{(*)+}\pi^0$ channels. The observation of such surprising states hinted that either the theoretical models are inadequate or the $D_{s0}^*(2317)^+$ and $D_{s1}(2460)^+$ mesons are not $c\bar{s}$ states but 4-quark systems, as corroborated by several observed anomalies. For instance, a significant deviation in the mass difference is measured:

$$m_{D_{s1}(2460)} - m_{D_{s0}^*(2317)} \approx 130\,\text{MeV}/c^2 \neq 40\,\text{MeV}/c^2 \approx m_{D_s^*(2573)} - m_{D_{s1}(2536)}$$

which is against the naive expectation of the $q\bar{q}$ models, where the coupling of the heavy c quark spin, after the spin-orbit coupling of the light quark $\bar{s}$, should equally affect the splittings of the two pairs of states with $\vec{J} = 1, 2$ and $\vec{J} = 0, 1$ respectively (fig. 1). On the contrary, the different mass splitting can be easily explained in the 4-quark picture. Moreover, in the heavy quark limit model, the following ratio R is expected ≈ 1, contrary to the measured value [18, 19]:

$$R = \frac{BR(B \to DD_{s1}(2460))}{BR(B \to DD_s^*)} \approx \frac{1}{3} \neq 1.$$

Again, the discrepancy could be explained by interpreting the $D_{s1}(2460)$ meson as a 4-quark state whose production is suppressed in $B \to DD_{s1}(2460)$ decays. Another anomaly is evident comparing the D_s^{*+} and $D_{s1}(2460)^+$ decay modes, shown in table I.

For the D_s^{*+} meson, the radiative decay mode is much more likely because it is not isospin-violating, unlike the $D_s^+\pi^0$ mode that violates the isospin conservation. Same remarks should be also valid for the $D_{s1}(2460)^+$ in a $c\bar{s}$ scenario, but its behavior is practically the opposite. Indeed, the isospin-violating $D_s^{*+}\pi^0$ decay mode is much more frequent than radiative $D_s^+\gamma$ mode, suggesting a 4-quark component ($c\bar{s}u\bar{u}$ or $c\bar{s}d\bar{d}$). It can also be noticed that the $D_{s1}(2460)^+$ decay channel spectrum is not complete. New decay channels, not observed so far, could be studied, such as Dalitz decays featured by two leptons in the final state, produced from a virtual photon. Currently, I am working on the search for muonic Dalitz decays, never seen so far:

$$D_{s1}(2460)^+ \to D_s^+ + \gamma^* \to D_s^+\mu^+\mu^-$$

I am using LHCb data in which a high purity sample of D_s^+ mesons has being reconstructed via the decay mode $D_s^+ \to K^+K^-\pi^+$. Later, the D_s^+ sample will be combined to two opposite charged muons. This search will benefit from large production cross and large efficiency of muons identification ($\approx$97%) in the final state.

TABLE I. – *Known decay modes and measured decay rates of the D_s^{*+} and $D_{s1}(2460)^+$ states* [19].

D_s^{*+}		$D_{s1}(2460)^+$	
Decay mode	Branching fraction (%)	Decay mode	Branching fraction (%)
$D_s^+\gamma$	93.5 ± 0.7	$D_s^+\gamma$	18 ± 4
$D_s^+\pi^0$	5.8 ± 0.7	$D_s^{*+}\pi^0$	48 ± 11
$D_s^+e^+e^-$	0.67 ± 0.16	$D_s^+\pi^+\pi^-$	4.3 ± 1.3
		Total	70 ± 12

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