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Excited Ω_c Baryons as $2S$ states

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The LHCb experiment has recently reported two excited Ω_c resonances decaying to $\Xi_c^+ K^-$, with masses about 3185 MeV and 3327 MeV. We discuss their assignment to $2S_{1/2}$ and $2S_{3/2}$ states, which can be compared with masses based on extrapolation from the observed $1S$ states. The agreement is not perfect, but weighs against an earlier alternative assignment. Consequences for the spin-averaged $2P$ states are discussed.

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I. INTRODUCTION

The LHCb experiment has reported the discovery of two new Ω_c^0 resonances at $3185.1 \pm 1.7^{+7.4}_{-0.9} \pm 0.2$ MeV and $3327.1 \pm 1.2^{+0.1}_{-1.3} \pm 0.2$ MeV [1]. Here the errors are statistical, systematic, and based on the uncertainty of the known Ξ_c^+ mass. Five previously observed Ω_c^0 states [2,3] were confirmed with higher statistics. These were interpreted as P-wave excitations of a charmed quark and an ss spin-1 diquark [4]; $J^P = 1/2^-$ for $\Omega_c(3000)^0$ and $\Omega_c(3050)^0$, $3/2^-$ for $\Omega(3065)^0$ and $\Omega_c(3090)^0$, and $5/2^-$ for $\Omega_c(3119)^0$, an assignment favored by lattice QCD [5]. A less favored picture takes the $\Omega_c(3090)^0$ and $\Omega_c(3119)^0$ as $2S_{1/2}$ and $2S_{3/2}$ [4].

In the present paper we identify the two new resonances as $\Omega_c(3185)^0 = 2S_{1/2}$ and $\Omega_c(3327) = 2S_{3/2}$, where the subscript denotes the total spin. The expected $2S$–$1S$ splitting is calculated and compared with the experiment in Sec. II, while a similar exercise is performed for the hyperfine splitting between the $1S$ and $2S$ states in Sec. III. The choice of the favored assignment [4] whereby the five narrow states are all taken as $1P$ is noted in Sec. IV. Consequences for the $2P$ levels are noted in Sec. V, while Sec. VI concludes.

II. $2S-1S$ SPLITTING

We are interested in the difference between $2S$ and $1S$ levels after account has been taken of hyperfine structure. To that end we note that in a system of spins s_1 and s_2 and total spin S the hyperfine interaction for $s_1 = s_2 = 1/2$ is proportional to $(1/4, -3/4)$ for $s_1 = (1, 0)$ while for $s_1 = 1$, $s_2 = 1/2$ it is proportional to $(1/2, -1)$. Thus, in quarkonium $(c\bar{c}, b\bar{b})$ systems one is interested in averages $(1/4)M(J=0) + (3/4)M(J=1)$ while in bound states of a spin-1/2 charmed quark and a spin-1 $\bar{s}\bar{s}$ antidiquark one is interested in averages $(1/3)M \times (J=1/2) + (2/3)M(J=3/2)$. We call these "spin-weighted averages".

In what follows we treat the $\Omega_c^0 = css$ states as two-body entities of a charmed quark c with mass $m_c = 1709$ MeV and a spin-1 ss diquark with $m_{ss} = 1095$ MeV [4]. The corresponding reduced mass, $\mu_{c,ss} = (m_c m_{ss})/(m_c + m_{ss}) = 667.4$ MeV, is not far from the charmonium reduced mass $\mu_{c\bar{c}} = m_c/2 = 854.5$ MeV. With the help of the bottomonium reduced mass $\mu_{b\bar{b}} = m_b/2 = 2521$ MeV and a power-law extrapolation for the predicted $2S$–$1S$ difference

$$\Delta = \overline{2S} - \overline{1S} = E_0 \mu^p \tag{1}$$

using the experimental values $\Delta_{c\bar{c}} = 605.3 \pm 0.3$ MeV, $\Delta_{b\bar{b}} = 572.3 \pm 1.3$ MeV, one finds $E_0 = 859.1$ MeV, $p = -0.05186$, and $\Delta_{c,ss} = 613.2$ MeV. Here one has calculated spin-weighted averages for quarkonia with relative weights (1/4, 3/4) for $J = (1/2, 3/2)$.

The observed value of Δ for the two new resonances, assuming their assignment to $2S_{J=1/2}$ and $(2S)_{J=3/2}$ states, is based on the masses in Table I ($1S$ values from Ref. [6]). To eliminate hyperfine contributions in the Ω_c states listed in

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TABLE I. Masses of $1S$ and proposed $2S$ Ω_c resonances in MeV.

	$M(nS_{1/2})$	$M(nS_{3/2})$	$\bar{M}(nS)$
1S	2695.2 ± 1.7	2765.9 ± 2.0	2742.3 ± 1.4
2S	$3185.1 \pm 1.7^{+7.4}_{-0.9} \pm 0.2$	$3327.1 \pm 1.2^{+0.1}_{-1.3} \pm 0.2$	$3279.8^{+2.7}_{-1.4}$

Table I we calculate spin-weighted averages of masses, with weight $1/3$ for $J = 1/2$ and $2/3$ for $J = 3/2$. The observed $2S$–$1S$ difference for the spin-weighted Ω_c states is then $(3279.8^{+2.7}_{-1.4} - 2742.3 \pm 1.4)$ MeV, or $(537.5^{+3.0}_{-2.0})$ MeV. This is to be compared with the value of 613 MeV obtained above by power-law extrapolation from charmonium and bottomonium.

III. HYPERFINE SPLITTING

The hyperfine splitting between the $\Omega_c^0(1S)_{1/2}$ and $\Omega_c^0(1S)_{3/2}$, using Particle Data Group [6] masses, is $2765.9 \pm 2.0 - 2695.2 \pm 1.7 = 70.7 \pm 2.6$ MeV. Normally one would expect it to be less for the $2S$ states (see, e.g., [7]) but the value assuming the two new states are $2S$ is $3327.1 \pm 1.2^{+0.1}_{-1.3} \pm 0.2 - [3185.1 \pm 1.7^{+7.4}_{-0.9} \pm 0.2] = 142.0^{+2.3}_{-7.8}$ MeV. One might ascribe part of this difference to final-state interactions, as the two new states have widths $50 \pm 7^{+10}_{-20}$ MeV ($J = 1/2$ candidate) and $20 \pm 5^{+13}_{-1}$ MeV ($J = 3/2$ candidate). Mass shifts of the same order as total widths can occur. The relative widths of the $J = 1/2$ and $J = 3/2$ $2S$ candidates are understandable: the $J = 1/2$ state decays to Ξ_c^+ via an S wave, while the $J = 3/2$ state decays to Ξ_c^+ via a more kinematically suppressed D wave. If the mass shift is greater for the state with the larger total width, it is natural to ascribe the larger-than-expected $2S$ hyperfine splitting mainly to a downward shift of the $J = 1/2$ state.

IV. FAVORED ASSIGNMENT OF FIVE NARROW STATES

In Ref. [4] the favored assignment of the five narrow Ω_c^0 peaks was to the five states of a spin-1 ss diquark and a spin-1/2 charmed quark in a relative P wave. A less likely assignment was to take the two highest narrow peaks to be $2S$, leaving two lower-mass P waves to be found.

With higher statistics, the new LHCb data show no evidence for the lower-mass P waves. Furthermore, taking $\Omega_c^0(3090)$ and $\Omega_c^0(3119)$ to be $2S$ states would exacerbate the difference between observed and predicted $1S$–$2S$ splittings, leaving the two new states without a credible assignment.

A possible solution to both the $2S$–$1S$ splitting and the hyperfine problems is to imagine that final-state interactions have lowered the mass of the $J = 1/2$ state, for which the final-state interactions are indeed greater, while leaving the $J = 3/2$ state mainly unshifted. Significant deviations from naive quark model predictions due to final-state interactions occur, for example, in the masses of $\Lambda(1405)$ and $D_s^0(2317)$ [6].

V. CONSEQUENCES FOR 2P LEVELS

The favored assignment of the two new levels to $2S_{1/2}$ and $2S_{3/2}$ entails a constraint on the spin-weighted average of the $2P$ levels. As above, we treat the $\Omega_c^0 = css$ states as two-body entities of a charmed quark c with mass $m_c = 1709$ MeV and a spin-1 ss diquark with $m_{ss} = 1095$ MeV [4]. The corresponding reduced mass, $\mu_{c,ss} = (m_c m_{ss})/(m_c + m_{ss})$ is 667.4 MeV. For an interquark potential proporional to $\ln r$ [8] or a small power of r [9] the quarkonium spectrum is universal up to a scale factor, so one may expect the excited Ω_c^* spectrum [Fig. 1(b) or 2(b)] to resemble that of charmonium [Fig. 1(a)] or bottomonium [Fig. 2(a)]. The mass difference between the spin-weighted averages $2\bar{S} = 3279.8^{+2.7}_{-1.4}$ MeV and $1\bar{P} = 3079.9 \pm 0.1$ MeV is represented by the nominal parameter $y = 200$ MeV, where possible systematic errors associated with different assignments are ignored. Some relevant comparisons are summarized in Tables II and III.

The pattern of level spacings for excited Ω_c^* levels is compared with those of charmonium and bottomonium in Figs. 1 and 2. We choose to take advantage of the mass cancellation in the ratio by fitting x/y rather than x. The similar shape of levels (aside from an additive constant) is a

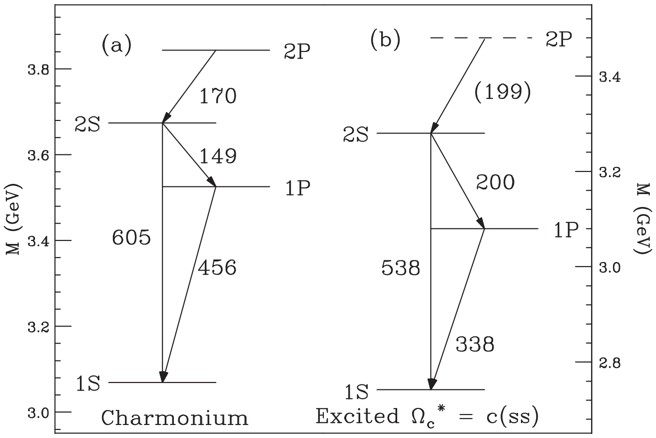

FIG. 1. Comparison of charmonium (a) and excited Ω_c^* (b) spectra. Numbers denote level spacings in MeV between spin-weighted averages. Predicted $2\bar{P} - 2\bar{S}$ spacing of 199 MeV (shown in parentheses) is for nominal choice of $y \equiv 2\bar{S} - 1\bar{P} = 200$ MeV.

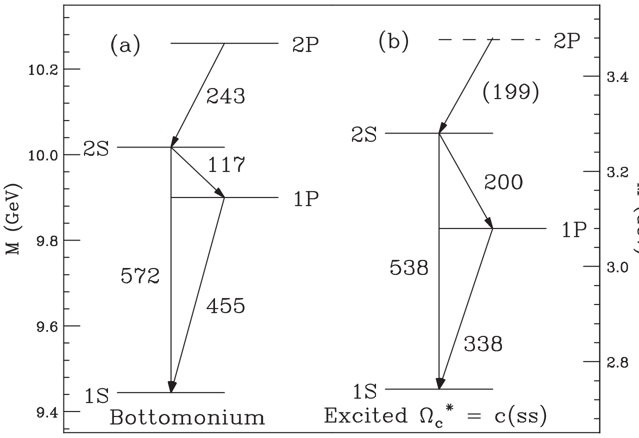

FIG. 2. Comparison of bottomonium (a) and excited Ω_c^* (b) spectra. Numbers denote level spacings in MeV between spin-weighted averages. Predicted $2\bar{P} - 2\bar{S}$ spacing of 199 MeV (shown in parentheses) is for nominal choice of $y \equiv 2\bar{S} - 1\bar{P} = 200$ MeV.

TABLE II. Inputs [6] and spin-weighted average masses (MeV).

	Charmonium		Bottomonium	
	$n = 1$	$n = 2$	$n = 1$	$n = 2$
n^1S_0	2983.9	3637.7	9398.7	9999
n^3S_1	3096.9	3686.1	9460.4	10023.4
$n\bar{S}$	3068.7	3674	9445.0	10017.3
n^3P_0	3414.71	3862	9859.44	10232.5
n^3P_1	3510.67	3872	9892.78	10255.46
n^1P_1	3525.37	⋯	9899.3	10259.8
n^3P_2	3556.17	3823	9912.21	10268.65
$n\bar{P}$	3525.3	3843.7	9899.9	10260.2

TABLE III. Comparison of excited Ω_c^* spectra with those of charmonium and bottomonium. The bold face entry denotes our prediction for the $2\bar{P} - 2\bar{S}$ splitting. It is obtained by interpolation as described in the text.

Spectrum	Reduced mass (MeV)	$x = 2\bar{P} - 2\bar{S}$ (MeV)	$y = 2\bar{S} - 1\bar{P}$ (MeV)	x/y
Excited Ω_c^*	667.4	**199.2**	200[a]	0.9959
Charmonium	854.5	169.7	148.7	1.141
Bottomonium	2521	242.9	117.4	2.069

[a] Nominal value.

feature of Refs. [8,9] for small-power-law or logarithmic potentials, when interpolating between charmonium and bottomonium, and also of qualitative validity for lighter quarks [10]. The value of x/y for excited Ω_c^* states may be interpolated between those of charmonium and bottomonium using a power-law dependence on reduced mass; $x/y = A\mu^p$ with the result (for the nominal choice $y = 200$ MeV)

$$A = 0.02783, \qquad p = 0.5501, \qquad x/y = 0.9959,$$
$$x = 199.2\ \text{MeV}, \tag{2}$$

or $2\bar{P} = 3479$ MeV. The dependence on the form of interpolation should be rather mild,as the reduced mass of the excited Ω_c^* is fairly close to that of charmonium. The predicted states may not be easy to confirm, as they will lie considerably above $\Xi_c^+ K^-$ threshold and thus may be quite broad.

VI. CONCLUSIONS

The two new excited Ω_c^0 states discovered by LHCb [1], at 3185 MeV and 3327 MeV, have been identified respectively as $2S_{J=1/2}$ and $2S_{J=3/2}$. The $1S$–$2S$ and hyperfine splittings, though smaller and larger, respectively, than expected, do not deviate enough from predicted values to jeopardize these assignments. Confirmation of our methods may be sought in other systems with no light quarks. The $b\bar{c}$ $(1S, 2S)$ system would be ideal except only the spin-zero $B_c(1S, 2S)$ masses are known, whereas only the $2S$–$1S$ mass difference is known for the B_c^* spin-one states [6,11–13]. A useful challenge to resolve this question would be the detection of the soft photon in $B_c^{*+} \to B_c^+ \gamma$.

When the two new states are interpreted as S-wave bound states of a charmed quark c and an antidiquark $(\bar{s}\,\bar{s})$, the spin-weighted average $2\bar{P}$ mass is predicted to lie about 200 MeV above the spin-weighted average $2\bar{S}$ mass $\bar{M} = 3280$ MeV.

ACKNOWLEDGMENTS

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