Heavy baryon spectroscopy

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Abstract. Masses of heavy baryons are calculated in the relativistic quark-diquark picture. Obtained results are in good agreement with available experimental data including recent measurements by the LHCb Collaboration. Possible quantum numbers of excited heavy baryon states are discussed.

1 Introduction

Recently significant experimental progress has been achieved in studying heavy baryon spectroscopy. Many new heavy baryon states have been observed. The main contribution was made by the LHCb Collaboration. Thus last year the amplitude analysis of the decay $\Lambda_b^0 \to D^0 p\pi^-$ was performed in the region of the phase space containing $D^0 p$ resonant contributions which revealed three Λ_c excited states and allowed to measure precisely their masses and decay widths [1]: the $\Lambda_c(2880)^+$ with the preferred spin $J = 5/2$; the new state $\Lambda_c(2860)^+$ with quantum numbers $J^P = 3/2^+$, its parity was measured relative to that of the $\Lambda_c(2880)^+$; the $\Lambda_c(2940)^+$ with the most likely spin-parity assignment $J^P = 3/2^-$ but other solutions with spins from 1/2 to 7/2 were not excluded. Then five new, narrow excited Ω_c states decaying to $\Xi_c^+ K^-$ were observed [2]: the $\Omega_c(3000)^0$, $\Omega_c(3050)^0$, $\Omega_c(3066)^0$, $\Omega_c(3090)^0$, and $\Omega_c(3119)^0$. These states were later confirmed by Belle [3]. Soon the discovery of the long-awaited doubly charmed baryon Ξ_{cc}^{++} was reported [4]. This year the new $\Xi_b(6227)^-$ resonance was observed as a peak in both the $\Lambda_b^0 K^-$ and $\Xi_b^0 \pi^-$ invariant mass spectra [5]. Finally, the first observation of two structures $\Sigma(6097)^\pm$ consistent with resonances in the final states $\Lambda_b^0 \pi^-$ and $\Lambda_b^0 \pi^+$ was reported by the LHCb [6].

In this talk we compare these new data with the predictions of the relativistic quark-diquark model of heavy baryons [7–9].

2 Relativistic quark-diquark model of heavy baryons

Our approach is based on the relativistic quark-diquark picture and the quasipotential equation. The interaction of two quarks in a diquark and the quark-diquark interaction in a baryon are described by the diquark wave function Ψ_d of the bound quark-quark state and by the baryon wave function Ψ_B of the bound quark-diquark state respectively. These wave functions satisfy the relativistic quasipotential equation of the Schrödinger type [7]

$$\left(\frac{b^2(M)}{2\mu_R} - \frac{\mathbf{p}^2}{2\mu_R}\right)\Psi_{d,B}(\mathbf{p}) = \int \frac{d^3q}{(2\pi)^3} V(\mathbf{p},\mathbf{q};M)\Psi_{d,B}(\mathbf{q}), \qquad (1)$$

where μ_R is the relativistic reduced mass, $b^2(M)$ is the center-of-mass relative momentum squared on the mass shell, $\mathbf{p}, \mathbf{q}$ are the off-mass-shell relative momenta, and M is the bound state mass (diquark or baryon).

The kernel $V(\mathbf{p}, \mathbf{q}; M)$ in Eq. (1) is the quasipotential operator of the quark-quark or quark-diquark interaction which is constructed with the help of the off-mass-shell scattering amplitude, projected onto the positive energy states. We assume that the effective interaction is the sum of the usual one-gluon exchange term and the mixture of long-range vector and scalar linear confining potentials, where the vector confining potential contains the Pauli term. The vertex of the diquark-gluon interaction takes into account the diquark internal structure and effectively smears the Coulomb-like interaction. The corresponding form factor is expressed as an overlap integral of the diquark wave functions. Explicit expressions for the quasipotentials of the quark-quark interaction in a diquark and quark-diquark interaction in a baryon can be found in [8]. All parameters of the model were fixed previously from considerations of meson properties and are kept fixed in the baryon spectrum calculations.

The quark-diquark picture of heavy baryons reduces a very complicated relativistic three-body problem to a significantly more simpler two step two-body calculation. First we determine the properties of diquarks. We consider a diquark to be a composite (qq') system. Thus diquark in our approach is not a point-like object. Its interaction with gluons is smeared by the form factor expressed through the overlap integral of diquark wave functions. These form factors enter the diquark-gluon interaction and effectively take diquark structure into account [8, 9]. Note that the ground state diquark composed from quarks with different flavours can be both in scalar and axial vector state, while the ground state diquarks composed from quarks of the same flavour can be only in the axial vector state due to the Pauli principle. Solving the quasipotential equation numerically we calculate the masses, determine the diquark wave functions and use them for evaluation of the diquark form factors. Only ground-state scalar and axial vector diquarks are considered for heavy baryons. While both qround-state as well as orbital and radial excitations of heavy diquarks are necessary for doubly heavy baryons, since the lowest excitations of such baryons originate from the excitations of the doubly heavy diquark.

Next we calculate the masses of heavy baryons in the quark–diquark picture [8, 9]. The heavy baryon is considered as a bound state of a heavy-quark and light-diquark. All excitations are assumed to occur between heavy quark and light diquark. On the other hand, the doubly heavy baryon is considered as a bound state of a light-quark and heavy-diquark. Both excitations in the quark-diquark system and excitations of the heavy diquark are taken into account. It is important to note that such approach predicts significantly less excited states of baryons compared to a genuine three-quark picture. We do not expand the potential of the quark–diquark interaction either in $p/m_{q,Q}$ or in p/m_d and treat both diquark and quark fully relativistically.

3 Heavy baryons

The calculated masses of heavy baryons are given in Tabs. 1-5. In the first column we show the baryon total isospin I, spin J and parity P. The second column lists the quark-diquark state. The next three columns refer to the charm and the last there columns to the bottom baryons. There we first give our prediction for the mass, then available experimental data [10]: baryon status and measured mass. The charm and bottom baryon states recently discovered by the LHCb Collaboration [1, 2, 4–6] are marked as new.

From Tabs. 1, 2 we see that the $\Lambda_c(2765)$ (or $\Sigma_c(2765)$), if it is indeed the Λ_c state, can be interpreted in our model as the first radial $(2S)$ excitation of the Λ_c. If instead it is the Σ_c state, then it can be identified as its first orbital excitation $(1P)$ with $J = \frac{3}{2}^-$ (see Tab. 2). The

Table 1. Masses of the Λ_Q ($Q = c, b$) heavy baryons (in MeV)

$I(J^P)$	Qd state	$Q = c$			$Q = b$		
		M	status	M^{exp}	M	status	M^{exp}
$0(\frac{1}{2}^+)$	1S	2286	****	2286.46(14)	5620	***	5619.51(23)
	2S	2769	*	2766.6(2.4)?	6089		
	3S	3130			6455		
	4S	3437			6756		
	5S	3715			7015		
	6S	3973			7256		
$0(\frac{1}{2}^-)$	1P	2598	***	2592.25(28)	5930	***	5912.11(26)
	2P	2983	***	$2944.8(^{1.4}_{1.5})$?	6326		
	3P	3303			6645		
	4P	3588			6917		
	5P	3852			7157		
$0(\frac{3}{2}^-)$	1P	2627	***	2628.1(6)	5942	***	5919.81(23)
	2P	3005			6333		
	3P	3322			6651		
	4P	3606			6922		
	5P	3869			7171		
$0(\frac{3}{2}^+)$	1D	2874	new	$2856.1.3(^{2.3}_{5.9})$	6190		
	2D	3189			6526		
	3D	3480			6811		
	4D	3747			7060		
$0(\frac{5}{2}^+)$	1D	2880	***	2881.75(35)	6196		
	2D	3209			6531		
	3D	3500			6814		
	4D	3767			7063		
$0(\frac{5}{2}^-)$	1F	3097			6408		
	2F	3375			6705		
	3F	3646			6964		
	4F	3900			7196		
$0(\frac{7}{2}^-)$	1F	3078			6411		
	2F	3393			6708		
	3F	3667			6966		
	4F	3922			7197		
$0(\frac{7}{2}^+)$	1G	3270			6598		
	2G	3546			6867		
$0(\frac{9}{2}^+)$	1G	3284			6599		
	2G	3564			6868		
$0(\frac{9}{2}^-)$	1H	3444			6767		
$0(\frac{11}{2}^-)$	1H	3460			6766		

Table 2. Masses of the Σ_Q ($Q = c, b$) heavy baryons (in MeV)

		$Q = c$			$Q = b$		
$I(J^P)$	Qd state	M	status	$M^{\exp}$	M	status	$M^{\exp}$
$1(\frac{1}{2}^+)$	$1S$	2443	****	2453.76(18)	5808	***	5807.8(2.7)
	$2S$	2901			6213		
	$3S$	3271			6575		
	$4S$	3581			6869		
	$5S$	3861			7124		
$1(\frac{3}{2}^+)$	$1S$	2519	***	2518.0(5)	5834	***	5829.0(3.4)
	$2S$	2936	***	$2939.3(^{1.4}_{1.5})$?	6226		
	$3S$	3293			6583		
	$4S$	3598			6876		
	$5S$	3873			7129		
$1(\frac{1}{2}^-)$	$1P$	2799	***	$2802(^4_7)$	6101		
	$2P$	3172			6440		
	$3P$	3488			6756		
	$4P$	3770			7024		
	$1P$	2713			6095		
	$2P$	3125			6430		
	$3P$	3455			6742		
	$4P$	3743			7008		
$1(\frac{3}{2}^-)$	$1P$	2798	***	$2802(^4_7)$	6096	new	6095.8(1.8)
	$2P$	3172			6430		
	$3P$	3486			6742		
	$4P$	3768			7009		
	$1P$	2773	*	2766.6(2.4)?	6087		
	$2P$	3151			6423		
	$3P$	3469			6736		
	$4P$	3753			7003		
$1(\frac{5}{2}^-)$	$1P$	2789			6084		
	$2P$	3161			6421		
	$3P$	3475			6732		
	$4P$	3757			6999		
$1(\frac{1}{2}^+)$	$1D$	3041			6311		
	$2D$	3370			6636		
$1(\frac{3}{2}^+)$	$1D$	3043			6326		
	$2D$	3366			6647		
	$1D$	3040			6285		
	$2D$	3364			6612		
$1(\frac{5}{2}^+)$	$1D$	3038			6284		
	$2D$	3365			6612		
	$1D$	3023			6270		
	$2D$	3349			6598		
$1(\frac{7}{2}^+)$	$1D$	3013			6260		
	$2D$	3342			6590		

Table 3. Masses of the Ξ_Q ($Q = c, b$) heavy baryons with the scalar diquark (in MeV)

$I(J^P)$	Qd state	$Q=c$			$Q=b$		
		M	status	$M^{\rm exp}$	M	status	$M^{\rm exp}$
$\frac{1}{2}(\frac{1}{2}^+)$	$1S$	2476	***	$2470.88(^{34}_{80})$	5803	***	5790.5(2.7)
	$2S$	2959			6266		
	$3S$	3323			6601		
	$4S$	3632			6913		
	$5S$	3909			7165		
$\frac{1}{2}(\frac{1}{2}^-)$	$1P$	2792	***	2792.8(1.2)	6120		
	$2P$	3179			6496		
	$3P$	3500			6805		
	$4P$	3785			7068		
	$5P$	4048			7302		
$\frac{1}{2}(\frac{3}{2}^-)$	$1P$	2819	***	2820.22(32)	6130		
	$2P$	3201			6502		
	$3P$	3519			6810		
	$4P$	3804			7073		
	$5P$	4066			7306		
$\frac{1}{2}(\frac{3}{2}^+)$	$1D$	3059	***	3055.9(0.4)	6366		
	$2D$	3388			6690		
	$3D$	3678			6966		
	$4D$	3945			7208		
$\frac{1}{2}(\frac{5}{2}^+)$	$1D$	3076	*	3079.9(1.4)	6373		
	$2D$	3407			6696		
	$3D$	3699			6970		
	$4D$	3965			7212		

$\Lambda_c(2880)$ baryon corresponds to the second orbital excitation ($2D$) with $J = \frac{5}{2}^+$ in accord with the LHCb analysis [1]. The other charmed baryon, denoted as $\Lambda_c(2940)$, probably has $I = 0$, since it was discovered in the pD^0 mass spectrum and not observed in pD^+ channel, but $I = 1$ is not ruled out [10]. If it is really the Λ_c state, then it could be both an orbitally and radially excited ($2P$) state with $J = \frac{1}{2}^-$, whose mass is predicted to be about 40 MeV heavier. A better agreement with experiment (within few MeV) is achieved, if the $\Lambda_c(2940)$ is interpreted as the first radial excitation ($2S$) of the Σ_c with $J = \frac{3}{2}^+$. The $\Sigma_c(2800)$ can be identified with one of the first orbital ($1P$) excitations of the Σ_c with $J = \frac{1}{2}^-$ or $\frac{3}{2}^-$ which have very close masses compatible with experimental value within errors (see Tab. 2). The new state $\Lambda_c(2860)$ with quantum numbers $\frac{3}{2}^+$ [1] can be well interpreted as second orbital excitation ($2D$ state). In the bottom sector the $\Lambda_b(5912)$ and $\Lambda_b(5920)$ correspond to the first orbitally excited ($1P$) states with $\frac{1}{2}^-$ and $\frac{3}{2}^-$, respectively. The new $\Sigma_b(6097)$ state [6] can be the first orbital excitation ($1P$) with quantum numbers $\frac{3}{2}^-$.

In the Ξ_Q baryon sector as we see from Tabs. 3,4 the $\Xi_c(2790)$ and $\Xi_c(2815)$ can be assigned to the first orbital ($1P$) excitations of the Ξ_c containing a scalar diquark with $J = \frac{1}{2}^-$ and $J = \frac{3}{2}^-$, respectively. On the other hand, the charmed baryon $\Xi_c(2930)$ can be considered as either the $J = \frac{1}{2}^-$, $J = \frac{3}{2}^-$ or $J = \frac{5}{2}^-$ state (all these states are predicted to have close masses) corresponding to the first orbital ($1P$) excitations of the Ξ_c' with an axial vector diquark. While the $\Xi_c(2980)$ can be viewed as the first radial ($2S$) excitation with $J = \frac{1}{2}^+$

Table 4. Masses of the Ξ_Q ($Q = c, b$) heavy baryons with the axial vector diquark (in MeV)

$I(J^P)$	Qd state	$Q=c$			$Q=b$		
		M	status	$M^{\rm exp}$	M	status	$M^{\rm exp}$
$\frac{1}{2}(\frac{1}{2}^+)$	$1S$	2579	***	2577.9(2.9)	5936	***	5935.02(5)
	$2S$	2983		2971.4(3.3)	6329		
	$3S$	3377			6687		
	$4S$	3695			6978		
	$5S$	3978			7229		
$\frac{1}{2}(\frac{3}{2}^+)$	$1S$	2649	***	2645.9(0.5)	5963	***	5955.33(13)
	$2S$	3026			6342		
	$3S$	3396			6695		
	$4S$	3709			6984		
	$5S$	3989			7234		
$\frac{1}{2}(\frac{1}{2}^-)$	$1P$	2936	*	2931(6)	6233		
	$2P$	3313			6611		
	$3P$	3630			6915		
	$4P$	3912			7174		
	$1P$	2854			6227	new	6226.9(2.1)
	$2P$	3267			6604		
	$3P$	3598			6906		
	$4P$	3887			7164		
$\frac{1}{2}(\frac{3}{2}^-)$	$1P$	2935	*	2931(6)	6234		
	$2P$	3311			6605		
	$3P$	3628			6905		
	$4P$	3911			7163		
	$1P$	2912			6224	new	6226.9(2.1)
	$2P$	3293			6598		
	$3P$	3613			6900		
	$4P$	3898			7159		
$\frac{1}{2}(\frac{5}{2}^-)$	$1P$	2929	*	2931(6)	6226	new	6226.9(2.1)
	$2P$	3303			6596		
	$3P$	3619			6897		
	$4P$	3902			7156		
$\frac{1}{2}(\frac{1}{2}^+)$	$1D$	3163			6447		
$\frac{1}{2}(\frac{3}{2}^+)$	$1D$	3167			6459		
	$1D$	3160			6431		
$\frac{1}{2}(\frac{5}{2}^+)$	$1D$	3166			6432		
	$1D$	3153			6420		
$\frac{1}{2}(\frac{7}{2}^+)$	$1D$	3147	*	3122.9(1.3)	6414		

of the Ξ_c', the $\Xi_c(3055)$ and $\Xi_c(3080)$ baryons can be interpreted as a second orbital ($2D$) excitations of the Ξ_c containing a scalar diquark with $J = \frac{3}{2}^+$ and $J = \frac{5}{2}^+$, and the $\Xi_c(3123)$ can be viewed as the corresponding ($2D$) excitation of the Ξ_c' with $J = \frac{7}{2}^+$. The recently observed excited bottom baryon $\Xi_b(6227)^-$ [5] can be one of the first radially excited states ($1P$) of the Ξ_b' baryon with the axial vector diquark and quantum numbers $\frac{1}{2}^-, \frac{3}{2}^-, \frac{5}{2}^-$ which are predicted to have very close masses.

Table 5. Masses of the Ω_Q ($Q = c, b$) heavy baryons (in MeV)

		$Q = c$			$Q = b$		
$I(J^P)$	Qd state	M	status	$M^{\rm exp}$	M	status	$M^{\rm exp}$
$0(\frac{1}{2}^+)$	$1S$	2698	***	2695.2(1.7)	6064	***	6046.4(1.9)
	$2S$	3088	new	$3090.2(^7_8)$	6450		
	$3S$	3489			6804		
	$4S$	3814			7091		
	$5S$	4102			7338		
$0(\frac{3}{2}^+)$	$1S$	2768	***	2765.9(2.0)	6088		
	$2S$	3123	new	$3119.1(^{1.0}_{1.1})$	6461		
	$3S$	3510			6811		
	$4S$	3830			7096		
	$5S$	4114			7343		
$0(\frac{1}{2}^-)$	$1P$	3055			6339		
	$2P$	3435			6710		
	$3P$	3754			7009		
	$4P$	4037			7265		
	$1P$	2966			6330		
	$2P$	3384			6706		
	$3P$	3717			7003		
	$4P$	4009			7257		
$0(\frac{3}{2}^-)$	$1P$	3054	new	$3065.6(^6_7)$	6340		
	$2P$	3433			6705		
	$3P$	3752			7002		
	$4P$	4036			7258		
	$1P$	3029	new	$3000.4(^4_6)$	6331		
	$2P$	3415			6699		
	$3P$	3737			6998		
	$4P$	4023			7250		
$0(\frac{5}{2}^-)$	$1P$	3051	new	$3050.2(^4_5)$	6334		
	$2P$	3427			6700		
	$3P$	3744			6996		
	$4P$	4028			7251		
$0(\frac{1}{2}^+)$	$1D$	3287			6540		
$0(\frac{3}{2}^+)$	$1D$	3298			6549		
	$1D$	3282			6530		
$0(\frac{5}{2}^+)$	$1D$	3297			6529		
	$1D$	3286			6520		
$0(\frac{7}{2}^+)$	$1D$	3283			6517		
$0(\frac{3}{2}^-)$	$1F$	3533			6763		

Masses of the Ω_c and Ω_b baryons are given in Tab. 5. The ground state ($1S$) masses were predicted [7] before experimental discovery and agree well with measured values. Recently observed [2] five new, narrow excited Ω_c are also in accord with our predictions. Three lighter states $\Omega_c(3000)^0$, $\Omega_c(3050)^0$ and $\Omega_c(3066)^0$ are well described as first orbital ($1P$) excitations with $J = \frac{3}{2}^-$, $\frac{5}{2}^-$ and $\frac{3}{2}^-$, respectively. These states are expected to be narrow. The remaining $1P$ states with $\frac{1}{2}^-$ are expected to be broad and thus can escape detection. The small peak

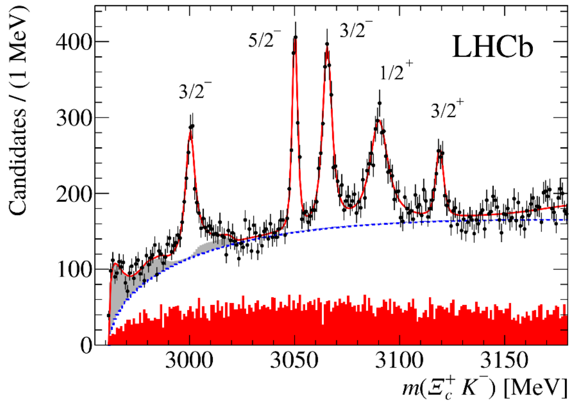

Figure 1. Proposed assignment of spins and parities of excited Ω_c states observed by LHCb Collaboration

in the low end of $\Xi_c^+ K^-$ mass distribution (see Fig. 1) can correspond to $\frac{1}{2}^-$ state with the predicted mass 2966 MeV (see Tab. 5). The remaining two heavier states $\Omega_c(3090)^0$ and $\Omega_c(3119)^0$ are naturally described as first radial ($2S$) excitations with quantum numbers $\frac{1}{2}^+$ and $\frac{3}{2}^+$, respectively. Their predicted masses coincide with the measured ones within a few MeV. The proposed assignment of spins and parities of excited Ω_c states observed by LHCb Collaboration is given in Fig. 1. In Tab. 6 we compare different quark model (QM), QCD sum rules (QCD SR), lattice QCD predictions and available experimental data for the masses of the Ω_c states.

Table 6. Comparison of theoretical predictions for the masses of the Ω_c states

State nL, J^P	our [8] RQM	[11] QM	[12] QM	[14] lattice	[13] lattice	[15] QCD SR	Experiment. PDG+LHCb
$1S, \frac{1}{2}^+$	2698	2718	2695	2648(28)	2695(28)	2685(123)	2695.2(1.7)
$2S, \frac{1}{2}^+$	3088	3152	3100	3294(73)		3066(138)	$3090.2(^{7}_{8})$
$1S, \frac{3}{2}^+$	2768	2776	2767	2709(32)	2781(25)	2769(89)	2765.9(2.0)
$2S, \frac{3}{2}^+$	3123	3190	3126	3355(92)		3119(114)	$3119.1(^{1.0}_{1.1})$
$1P, \frac{1}{2}^-$	2966	2977	3028	2995(46)	3015(45)		
$1P, \frac{1}{2}^-$	3055	2990	3011				
$1P, \frac{3}{2}^-$	3054	2986	2976	3016(69)			$3065.6(^{6}_{7})$
$1P, \frac{3}{2}^-$	3029	2994	2993				$3000.4(^{4}_{6})$
$1P, \frac{5}{2}^-$	3051	3014	2947				$3050.2(^{4}_{5})$

4 Doubly heavy baryons

Mass spectra of doubly heavy baryons was calculated in the light-quark–heavy-diquark picture in [9]. The light quark was treated completely relativistically, while the expansion in the inverse heavy quark mass was used. Tab. 7 shows the Ξ_{cc} mass spectrum. Excitaions inside doubly heavy diquark and light-quark–heavy-diquark bound systems are taken into account. We use the notations $(n_d L n_q l) J^P$, where we first show the radial quantum number of the diquark ($n_d = 1, 2, 3\ldots$) and its orbital momentum by a capital letter ($L = S, P, D\ldots$) , then

Table 7. Mass spectrum of Ξ_{cc} baryons (in GeV)

State $(n_d L n_q l)J^P$	Mass our	Mass [16]	State $(n_d L n_q l)J^P$	Mass our	Mass [16]
$(1S\,1s)\frac{1}{2}^+$	3.620	3.478	$(1P1s)\frac{1}{2}^-$	3.838	3.702
$(1S\,1s)\frac{3}{2}^+$	3.727	3.61	$(1P1s)\frac{3}{2}^-$	3.959	3.834
$(1S\,1p)\frac{1}{2}^-$	4.053	3.927	$(2S\,1s)\frac{1}{2}^+$	3.910	3.812
$(1S\,1p)\frac{3}{2}^-$	4.101	4.039	$(2S\,1s)\frac{3}{2}^+$	4.027	3.944
$(1S\,1p)\frac{1}{2}^{\prime -}$	4.136	4.052	$(2P1s)\frac{1}{2}^-$	4.085	3.972
$(1S\,1p)\frac{5}{2}^-$	4.155	4.047	$(2P1s)\frac{3}{2}^-$	4.197	4.104
$(1S\,1p)\frac{3}{2}^{\prime -}$	4.196	4.034	$(3S\,1s)\frac{1}{2}^+$	4.154	4.072

Table 8. Mass spectrum of ground states of doubly heavy baryons (in GeV). $\{QQ\}$ denotes the diquark in the axial vector state and $[QQ]$ denotes diquark in the scalar state

Baryon	Quark content	J^P	our [9]	[16]	[17]	[18]	[19]	[11]	[20]
Ξ_{cc}	$\{cc\}q$	$\frac{1}{2}^+$	3.620	3.478	3.66	3.69	3.510	3.676	3.627(12)
Ξ^*_{cc}	$\{cc\}q$	$\frac{3}{2}^+$	3.727	3.61	3.74		3.548	3.753	3.690(12)
Ω_{cc}	$\{cc\}s$	$\frac{1}{2}^+$	3.778	3.59	3.74	3.86	3.719	3.815	
Ω^*_{cc}	$\{cc\}s$	$\frac{3}{2}^+$	3.872	3.69	3.826		3.746	3.876	
Ξ_{bb}	$\{bb\}q$	$\frac{1}{2}^+$	10.202	10.093	10.34	10.16	10.130	10.340	10.162(12)
Ξ^*_{bb}	$\{bb\}q$	$\frac{3}{2}^+$	10.237	10.133	10.37		10.144	10.367	10.184(12)
Ω_{bb}	$\{bb\}s$	$\frac{1}{2}^+$	10.359	10.18	10.37	10.34	10.422	10.454	
Ω^*_{bb}	$\{bb\}s$	$\frac{3}{2}^+$	10.389	10.20	10.40		10.432	10.486	
Ξ_{cb}	$\{cb\}q$	$\frac{1}{2}^+$	6.933	6.82	7.04	6.96	6.792	7.011	6.914(13)
Ξ'_{cb}	$[cb]q$	$\frac{1}{2}^+$	6.963	6.85	6.99		6.825	7.047	6.933(12)
Ξ^*_{cb}	$\{cb\}q$	$\frac{3}{2}^+$	6.980	6.90	7.06		6.827	7.074	6.969(14)
Ω_{cb}	$\{cb\}s$	$\frac{1}{2}^+$	7.088	6.91	7.09	7.13	6.999	7.136	
Ω'_{cb}	$[cb]s$	$\frac{1}{2}^+$	7.116	6.93	7.06		7.022	7.165	
Ω^*_{cb}	$\{cb\}s$	$\frac{3}{2}^+$	7.130	6.99	7.12		7.024	7.187	

the radial quantum number of the light quark ($n_q = 1, 2, 3\dots$) and its orbital momentum by a lowercase letter ($l = s, p, d\dots$), and at the end the total angular momentum J and parity P of the baryon. In Tab. 8 we compare different theoretical predictions for the ground state masses of the doubly heavy baryons. Our prediction (2002) for the mass of the Ξ_{cc} baryon [9] excellently agrees with its mass recently measured (2017) by the LHCb Collaboration [6]:

$$M^{\rm exp}(\Xi_{cc}^{++}) = 3621.40 \pm 0.72 \pm 0.27 \pm 0.14 \text{ MeV}.$$

5 Conclusions

Recent observations of excited charm and bottom baryons confirm predictions of the relativistic heavy-quark–light-diquark model of heavy baryons [7, 8]. The new state $\Lambda_c(2860)$ is in accord with the predicted $1D$- state with $J^P = \frac{3}{2}^+$. The experimentally preferred quantum numbers $J^P = \frac{5}{2}^+$ of $\Lambda_c(2880)$ agree with our assignment of this state to $1D$- state with $J^P = \frac{5}{2}^+$. The $\Lambda_b(5912)$ and $\Lambda_b(5920)$ are well described as the first orbitally excited ($1P$) states with $\frac{1}{2}^-$ and $\frac{3}{2}^-$, respectively. The new $\Sigma_b(6097)$ state can be the first orbital excitation

$(1P)$ with quantum numbers $\frac{3}{2}^-$. The recently observed excited bottom baryon $\Xi_b(6227)^-$ can be one of the first radially excited states $(1P)$ of the Ξ_b' baryon with the axial vector diquark and quantum numbers $\frac{1}{2}^-$, $\frac{3}{2}^-$, $\frac{5}{2}^-$ which are predicted to have very close masses. Observation of five new narrow Ω_c states in the mass range 3000-3200 MeV agrees with our prediction of orbitally excited $1P$-states and radially excited $2S$-states in this mass region: $\Omega_c(3000)$, $\Omega_c(3066)$, $\Omega_c(3050)$ can be $1P$-states with $J^P = \frac{3}{2}^-, \frac{3}{2}^-, \frac{5}{2}^-$ while $\Omega_c(3090)$ and $\Omega_c(3119)$ states are most likely the first radially excited $2S$ states with $J^P = \frac{1}{2}^+, \frac{3}{2}^+$.

In the doubly heavy baryon sector, the mass of recently observed Ξ_{cc}^{++} baryon is in excellent agreement with our prediction made more than 15 years ago [9]. Masses of ground state doubly charm baryons are predicted to be in 3.5 - 3.9 GeV range. Masses of ground state doubly bottom baryons are predicted to be in 10.1 - 10.5 GeV range. Masses of ground state bottom-charm baryons are predicted to be in 6.8 - 7.2 GeV range. Rich spectra of narrow excited states below strong decay thresholds are expected. We strongly encourage experimenters to search for new excited states of heavy baryons and especially for doubly heavy baryons.

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