Heavy-flavor baryons

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Abstract. This is a contribution to the review “50 Years of Quantum Chromodynamics” edited by F. Gross and E. Klempt, to be published in EPJC. The contribution reviews the properties of baryons with one heavy flavor: the lifetimes of ground states and the spectrum of excited states. The importance of symmetries to understand the excitation spectrum is underlined. An overview of searches for pentaquarks is given.

1 Introduction

Baryons with one heavy quark $Q$ and a light diquark $qq$ provide an ideal place to study diquark correlations and the dynamics of the light quarks in the environment of a heavy quark. The heavy quark is almost static and provides the color source to the light quarks. Here, we attempt to understand the dynamics leading to the spectrum of baryons with one heavy quark.

The Review of Particle Physics [1] lists 28 charmed baryons (16 with known spin-parity) and 22 bottom baryons (15 with known spin-parity). One doubly charmed state has been detected, the ground state $\Xi^{++}$ (its isospin partner $\Xi^{++}$ is known as well, with poor evidence and one star in RPP, but we do not count isospin partners separately.) In the decays of the lightest bottom baryon, $\Lambda_b$, the corresponding CKM matrix element is $2.7\pm 0.14\pm 2.4\pm 26$. The search for further states and attempts to understand the underlying dynamics of heavy baryons are active fields in particle physics. New information can be expected from the upgrades of LHC, BELLE and J-PARC, and from the new FAIR facility at GSI.

2 Ground states of heavy baryons

2.1 Masses and lifetimes

Table 1 presents masses and life times of the ground states of heavy baryons containing a $b$-quark. Naively, one could expect all these life times to represent the life time of the $B^0$ meson. This life time is $\tau_{B^0}=(1519\pm4)\,\text{fs}$. Indeed, all life times agree within $\sim 10\%$ percent.

This is not at all the case when the $b$-quark is replaced by a $c$-quark (see Table 2). The $D^0$ has a life time $\tau_{D^0}=(410.3\pm1.0)\,\text{fs}$, the $D^+$ has $\tau_{D^+}=(1033\pm5)\,\text{fs}$. The life times of charmed baryons are spread over a wide range and do not agree with the life times of $D$ mesons. In addition to the decay of the $c$-quark, the $cd$ pair in a $D^0$ meson can annihilate into a $W^+$, a process forbidden for the $D^+$.

Table 1. Masses and lifetimes of baryon ground states with one $b$-quark. The second line gives the mass in MeV, the third line the life time in fs.

| $A_b^-$ | $\Xi_b^-$ | $\Xi_b^+$ | $\Omega_b^-$ |
|--------|----------|----------|-------------|
| 5619.60±0.17 | 5797.0±0.6 | 5791.9±0.5 | 6045.2±1.2 |
| 1464±11 | 1572±40 | 1480±0.030 | 1640±180 |

Table 2. Masses and lifetimes of baryon ground states with one $c$-quark. The second line gives the mass in MeV, the third line the life time in fs.

| $A^0$ | $\Xi^+$ | $\Xi^0$ | $\Omega^-$ |
|-------|--------|--------|-------|
| 2286.46±0.14 | 2467.71±0.23 | 2470.44±0.2 | 2695.2±1.7 |
| 201.5±2.7 | 453±5 | 151.9±2.4 | 268±26 |

$\tau_{D^0}=(410.3\pm1.0)\,\text{fs}$, the $D^+$ has $\tau_{D^+}=(1033\pm5)\,\text{fs}$. The life times of charmed baryons are spread over a wide range and do not agree with the life times of $D$ mesons. In addition to the decay of the $c$-quark, the $cd$ pair in a $D^0$ meson can annihilate into a $W^+$, a process forbidden for the $D^+$. In $B$ decays, the corresponding CKM matrix element is small, and this effect is suppressed. Further significant corrections are required to arrive at a consistent picture for the decays of charmed mesons and baryons. The authors of Ref. [3] have performed an extensive study of the lifetimes within the heavy quark expansion, and have included all known corrections. The impact of the charmed-quark mass and of the wavefunctions of charmed hadrons were carefully studied. Then, qualitative agreement between their calculations and the experimental data was achieved.

The first state with two charmed quarks, the $\Xi_c^{++}$ was reported by the SELEX collaboration in two decay modes at a mass of $(3518.9\pm0.9)\,\text{MeV}$ and with 5.6$\sigma$ [5, 6]. In later searches, this state was never confirmed. The LHCb collaboration found its doubly charged partner $\Xi_c^{+±}$ [7]. Its mass is $(3621.6\pm0.4)\,\text{MeV}$, its life time $(25.6±2.7)\,\text{fs}$. 

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Later, the LHCb collaboration reported evidence for a $\Xi_{cc}^+$ baryon at $(3623.0 \pm 1.4)$ MeV [8]. It is seen with 3-4$\sigma$ only but its mass is better compatible with an interpretation of $\Xi_{cc}^+$ and $\bar{\Xi}_{cc}^+$ as isospin partners. A search for the $\Xi_{bc}$ remained unsuccessful [9].

2.2 The flavor wave function: SU(4)

In this contribution we discuss baryons with one heavy-quark flavor, with either a charm or a bottom quark. Overall, we consider five quarks, $u,d,s,c,b$, but we will not discuss baryons with one light ($q = u,d,s$) and two different heavy quarks like $\Xi_{cb}^+ = (ucb)$. Thus we can restrict ourselves to SU(4). The four quarks have very different masses, and the SU(4) symmetry is heavily broken, nevertheless it provides a guide to classify heavy-quark baryons.

Three-quark baryons can classified according to

$$4 \otimes 4 \otimes 4 = 20_s \oplus 20_m \oplus 20_n \oplus 4_a$$

into a fully symmetric 20-plet, two 20-plets of mixed symmetry and a fully antisymmetric 4-plet. In states with one heavy quark only, there is one light quark pair. The light diquark can be decomposed

$$3 \otimes 3 = 3_a \oplus 6_s$$

The light diquark in the 6-plet is symmetric, in the 3-plet antisymmetric.

Figure 1b shows the mixed symmetry 20-plet of heavy baryons. In the ground state they have $J = 1/2$. Baryons with one heavy quark occupy the second layer. The 6-plet and the 3-plet are indicated. The sextet in the first floor has a a symmetric light-quark pair, the two light-heavy quark pairs are then antisymmetric in flavor. The 3-plet in the first floor has an antisymmetric light-quark pair, the light-heavy quark pairs are then symmetric in flavor.

Finally, there is a fully anti-symmetric 4-plet. It is shown in Fig. 1c. Ground-state baryons have a symmetric spatial wave function. A spin wave function of three fermions has mixed symmetry. A fully symmetric, a fully antisymmetric and a mixed-symmetry wave function cannot be coupled to a fully symmetric wave function. Hence ground-state baryons cannot be in the 4-plet. Only excited baryons can have a fully antisymmetric flavor wave function. Below, in Section 5 the wave functions and their symmetries are discussed in more detail.

3 Excited baryons: Selected experimental results

3.1 BaBar, BELLE and LHCb:

Most information on heavy baryons stems from three experiments, BaBar, BELLE and LHCb even though many discoveries had already been made before with the Split-Field-Magnet, by the SELEX, UA and LEP experiments at CERN, and by the CDF experiment at FERMILAB. BaBar at SLAC (US) and BELLE at KEK (Japan) study the decays of $B$ mesons produced in asymmetric $e^+e^-$ storage rings with beam energies of 9 (KEK: 7) GeV for electrons and 3.1 (KEK: 4) GeV for positrons resulting in a center-of-mass energy equal to the $\Upsilon(4S)$ mass of 10.58 GeV. The LHCb experiment is placed at the Large Hadron Collider at CERN operating at $\sqrt{s} = 13.6$ GeV. The experiment is a single-arm forward spectrometer covering the pseudorapidity range $2 \leq \eta \leq 5$. It is designed for the study of particles containing $b$ or $c$ quarks. All three detectors have vertex reconstruction capabilities; BaBar
and BELLE track charged particles in tracking chambers placed in the 1.5 T magnetic field of a superconducting solenoid. Particle identification is provided by a measurement of the specific ionization and by detection of the Cherenkov radiation in reflecting ring imaging Cherenkov detectors. CsI(Tl)-crystal electromagnetic calorimeters allow for energy measurements of electrons and photons. LHCb is equipped with silicon-strip detector located upstream and downstream of a dipole magnet with a bending power of about 4 Tm. Photons, electrons and hadrons are identified by a calorimeter system consisting of scintillating counters and pre-shower detectors, and an electromagnetic and a hadronic calorimeter. Muons are identified by a system composed of alternating layers of iron and multiwire proportional chambers.

In the following we discuss three important results from these experiments that demonstrate the capabilities of the detectors.

3.2 Observation of $\Omega_c^0(2770)$ decaying to $\Omega_c^0\gamma$ by BaBar:

The Babar experiment studied the inclusive reaction $e^+e^-\rightarrow\Omega_c^{\pm}X$ where $X$ denote the recoiling particles. $\Omega_c^0$ baryons are identified via different decay modes and reconstructed with a mass resolution $\sigma_{\text{RMS}} = 13$ MeV. The $\gamma$ is reconstructed in the $\Omega_c^0$ CsI(Tl) calorimeter. Figure 2 shows the reconstructed $\Omega_c^0$ and the $\Omega_c^{*0}$ in its $\Omega_c^{*0}\rightarrow\Omega_c^0\gamma$ decay. Obviously, the $\Omega_c^{*0}(2770)$ is equivalent to $\Delta^0(1232)$ with the $u,d,d$ quarks exchanged by $c,s,s$, and the transition corresponds to the $\Delta(1232)\rightarrow N\gamma$ decay.

Fig. 2. Left: The invariant mass distributions of $\Omega_c^0$ candidates in their decay to $\Omega_c^{*0}(\text{a}), \Omega_c^{*0}\pi^0(\text{b}), \Omega_c^{*0}\pi^-\pi^+(\text{c}), \Xi^-K^+\pi^-\pi^+(\text{d}). M_{\text{HP}}$ is the reconstructed mass of $\Omega_c^0$ candidates, $X_h$ denotes the daughter hyperon. Right: Invariant mass distribution of $\Omega_c^0\rightarrow \Omega_c^{0}\gamma$ for the individual $\Omega_c^0$ decay modes (a-d) and for the sum (e). (Adapted from [10].)

3.3 First determination of the spin and parity of the charmed-strange baryon $\Xi_c^+(2970)$ by BELLE.

The BELLE collaboration identified $\Xi_c^+(2970)$ in the decay chain $\Xi_c^+(2970)\rightarrow\Xi_c^0(2645)\pi^+\rightarrow\Xi_c^+\pi^-\pi^+; \Xi_c^+$ is reconstructed from its decay into $\Xi_c^\pi^+\pi^+$. Due to its mass, $\Xi_c^0(2645)$ is likely the spin excitation with $J^P = 3/2^+$ of the $J^P = 1/2^+$ ground state $\Xi_c^0$. The helicity angle in the primary decay, i.e. the angle between the $\pi^+$ and the opposite of the boost direction in the c.m. frame both calculated in the $\Xi_c^+$ rest frame, proved to be insensitive to some likely $J^P$ combinations. However, the predictions for different $J^P$’s vary significantly for the angular distributions in the secondary decay (see Fig. 3).

The analysis shows that quantum numbers $J^P = 1/2^+$ are preferred for $\Xi_c^+(2970)$. These are the quantum numbers of the Roper resonance. The BELLE collaboration noted that its mass difference to the $\Xi_c^-$ ground state is about 500 MeV. The same excitation energy is required to excite the Roper resonance $N(1440)$, the $\Lambda(1600)$ and the $\Sigma(1660)$, all with $J^P = 1/2^+$.

Fig. 3. Left: The $\Xi_c^+\pi^-\pi^+$ invariant mass distribution for events in which the $\Xi_c^+\pi^-\pi^+$ invariant mass is compatible with the $\Xi_c^0(2645)$ mass. Right: The helicity angle $\theta_h$ between the direction of the $\pi^-$ relative to the opposite direction of the $\Xi_c^+(2970)$ in the rest frame of the $\Xi_c^0(2645)$. (Adapted from Ref. [11].)

3.4 First observation of excited $\Omega_b$ states by LHCb.

The LHCb collaboration searched for narrow resonances in the $\Xi_b^0K^-$ invariant mass distribution [12]. The $\Xi_b^0$ has a lifetime of $(1.48\pm0.03)\times10^{-12}$ s, $c\tau \approx 500\mu$m, which is...
sufficiently long to separate the interaction and the decay vertices. Four peaks can be seen (Fig. 4), which correspond to excited states of $\Omega_c$. With the given statistics, quantum numbers can not yet be determined.

4 The mass spectrum of excited heavy baryons

Figure 5 shows the mass spectrum of heavy baryons with a single charm or bottom quark. Established light baryons with strangeness are shown for comparison. The quantum numbers of low-mass heavy baryons are mostly known, for higher-mass states this information is often missing. The masses are given as excitation energies above the $\Lambda$ ($\Lambda_c$, $\Lambda_b$) mass.

At the first glance, the spectrum looks confusing. The $\Lambda$ spectrum is crowded, there is a low-mass negative-parity spin doublet, a second doublet – at about the same mass as a $\Sigma$ spin doublet – a pair with $J^P = 1/2^-$ and $5/2^-$ where a $3/2^-$ state seems to be missing, and then a positive-parity doublet with $J^P = 3/2^+, 5/2^+$. In the $\Lambda_c$ spectrum, the higher-mass negative-parity states and the positive-parity doublet are inverted in mass. The $3/2^- - 1/2^+$ hyperfine splitting decreases rapidly when going from $\Sigma$ and $\Xi$ to $\Sigma_c$ and $\Xi_c$ and from $\Sigma_b$ and $\Xi_b$. It is interesting to note that a similar pattern is observed in mesons: the hyperfine splitting decreases when going from $\rho \sim \pi$ to $D^* - D$ and to $B^* - B$. Also, there is one $\Xi_c^+ 1/2^+$ ground state but two states for $\Xi_{bc}^-$ and $\Xi_{cb}^-$. The lowest-mass $\Omega$ has $J^P = 3/2^+$, in the charm sector, two low-mass $\Omega_c$ states are known with $J^P = 1/2^+$ and $3/2^+$, the $\Omega_b$ spectrum has just one low-mass state with $J^P = 1/2^+$.\footnote{This inversion was predicted by Capstick and Isgur long before the states were discovered\cite{13}}

5 Heavy baryons as three-quark systems

5.1 The spatial wave function

The orbital wave functions of excited states are classified into two kinds of orbital excitations, the $\lambda$-mode and the $\rho$-mode. In heavy baryons with one heavy quark, the $\lambda$-mode is the excitation of the coordinate between the heavy quark and the light diquark, and the $\rho$-mode is the excitation of the diquark cluster. In light-baryon excitations, the $\lambda$ and $\rho$ oscillators are mostly both excited, e.g. to $l_\lambda = 1$, $l_\rho = 0$ and $l_\lambda = 0$, $l_\rho = 1$, the two components of the wave function having a relative $+$ or $-$ sign. In heavy baryons with one heavy quark, the mixing between these two configurations is small.

The two oscillators have different reduced masses, $m_\rho$ and $m_\lambda$:

$$m_\rho = \frac{m_q}{2}, \quad m_\lambda = \frac{2m_qm_Q}{2m_q + m_Q}. \quad (3)$$

The ratio of harmonic oscillator frequencies is then given by

$$\frac{\omega_\lambda}{\omega_\rho} = \sqrt{\frac{1}{3}} \leq 1. \quad (4)$$

In the heavy-quark limit ($m_Q \to \infty$), the excitation energies in the $\lambda$ oscillator are reduced by a factor $\sqrt{3}$.

5.2 Diquarks

We first consider the light diquark. The two light quarks can have either the symmetric flavor structure $6_F$ or the antisymmetric flavor structure $3_F$. The spin of the light diquark can be $s_{qq} = s_I = 1$ or $s_I = 0$ leading to a symmetric or an antisymmetric spin wave function. The color part of the wave function is totally antisymmetric. Hence flavor and spin wave functions are linked. In an $S$-wave, scalar (“good” or $g$) and axial-vector (“bad” or $b$) diquarks can be formed. The intrinsic quark spins couple to the internal orbital angular momentum $l_\rho$, leading to excited diquarks with orbital excitations:

\[
\begin{align*}
(l_\rho = 0, S) \quad & \{ s_I = 0 \ (A), \ 3_F \ (A), \ j_{qq} = 0, \ (g) \\
& \{ s_I = 1 \ (S), \ 6_F \ (S), \ j_{qq} = 1 \} \quad (b)
\end{align*}
\]

\[
\begin{align*}
(l_\rho = 1, A) \quad & \{ s_I = 0 \ (A), \ 6_F \ (S), \ j_{qq} = 1 \} \quad (g) \\
& \{ s_I = 1 \ (S), \ 3_F \ (A), \ j_{qq} = 0 \} \quad (b)
\end{align*}
\]

\[
\begin{align*}
(l_\rho = 2, S) \quad & \{ s_I = 0 \ (A), \ 3_F \ (A), \ j_{qq} = 2 \} \quad (g) \\
& \{ s_I = 1 \ (S), \ 6_F \ (S), \ j_{qq} = 1 \} \quad (b)
\end{align*}
\]

\[
\cdots
\]

where we have denoted the total angular momentum of the light diquark as $j_{qq}$.

5.3 Coupling of angular momenta

Figure 4 shows how the orbital angular momentum and the diquark spin couple to the total diquark angular momentum $j_i$. This in turn couples to the heavy-quark spin.
Due to the conservation of the total angular momentum, the angular momentum carried by the light quarks is conserved. Hence all interactions which depend on the spin of the heavy quark disappear. Thus, the mass difference within a spin doublet with, e.g., \(J^P = 3/2^+\) and \(1/2^+\), will disappear in the heavy-quark limit. Indeed, the mass differences

\[
M_{\Sigma(1550)/3/2^+} - M_{\Omega(1950)/2} = 230\text{ MeV}
\]

\[
M_{\Sigma(2550)/3/2^+} - M_{\Sigma(2455)/2} = 65\text{ MeV}
\]

\[
M_{\Sigma(5850)/3/2^-} - M_{\Sigma(5820)/2} = 20\text{ MeV}
\]

decrease as \(m_Q\) becomes large.

### 6 A guide to the literature

The first prediction of the full spectrum of baryons including charmed and bottom baryons was presented by Capstick and Isgur [13], three years before the first baryon with bottomness was discovered. The publication remained a guideline for experimenters for now 36 years! Capstick and Isgur used a relativized quark model with a confining potential and effective one-gluon exchange. Based on the quark model, further studies of the mass spectra of heavy baryons were performed. They are numerous, and only a selection of papers can be mentioned here.

Ebert, Faustov and Galkin calculated the mass spectra for orbital and radial excitations and constructed Regge trajectories [15]. Yu, Li, Wang, Lu, and Ya [16] calculated the mass spectra and decays of heavy baryons excited in the \(\lambda\)-mode. Li, Yu, Wang, Lu, and Gu [17] restricted the calculation - again based on the relativized quark model - to the \(\Xi_c\) and \(\Xi_b\) families. In their model, all excitations are in the \(\lambda\)-mode.

Migura, Merten, Metsch, and Petry [18] calculated excitations of charmed baryons within a relativistically covariant quark model based on the Bethe-Salpeter-equation in instantaneous approximation. Interactions are given by a linearly rising three-body confinement potential and a
flavor dependent two-body force derived from QCD instanton effects. Valcarce, Garcilazo and Vijande \cite{19} performed a comparative Faddeev study of heavy baryons with nonrelativistic and relativistic kinematics and different interacting potentials that differ in the description of the hyperfine splitting. The authors conclude that the mass difference between members of the same SU(3) configuration, either 3F or 6F, is determined by the interaction in the light-heavy quark subsystem, and the mass difference between members of different representations is mainly determined by the dynamics of the light diquark.

Chen, Wei and Zhang \cite{20} derive a mass formula in a relativistic flux tube model to calculate mass spectra for Λ and Ξ heavy baryons and assign quantum numbers to states whose quantum numbers were not known. Faustov and Galkin \cite{21} assigned flavor- and symmetry dependent masses and form factors to diquarks and calculated the masses of heavy baryons within a relativistic quark-diquark picture. Quantum numbers are suggested for the Ωc excitations \cite{22,23} and other states with unknown spin-parities. A further diquark model, again with adjusted diquark masses, is presented by Kim, Liu, Oka, and Suzuki \cite{24} exploiting a chiral effective theory of scalar and vector diquarks according to the linear sigma model.

QCD sum rules have been exploited to study P-wave heavy baryons and their decays within the heavy quark effective theory (see \cite{25} and refs. therein). The low-lying spectrum of charmed baryons has also been calculated in lattice QCD with a pion mass of 156 MeV \cite{26}. The results - comparing favorably with the data - are compared to earlier lattice studies that are not discussed here.

All calculations reproduce the observed spectrum with good success, with a large number of parameters. For the reader, it is often not easily seen what are the main driving forces that generate the mass spectrum. Clearly, a confinement potential is mandatory, spin dependent forces are necessary. In the following phenomenological part we try to identify the leading effects driving the resonance spectrum.

### 7 Phenomenology of heavy baryons

We start with a simple observation: masses of baryons increase when a u or d quark is replaced by an s quark (see Table 4). For light baryons, this is known as U-spin rule. The constituent s-quark mass decreases in heavy baryons. The difference of current quark masses is

\[ m_s - m_n \approx 124 \text{ MeV}. \]

In Table 5 we show the mass difference of the lowest-mass \( J^P = 3/2^- \) states with \((u, d, s, c)\) or \((u, d, s, b)\) quarks and the \( J^P = 1/2^+ \) ground states: The mass differences are surprisingly small. The \( N(1520) - N \) mass difference is 580 MeV, much larger than the mass differences seen here. In the table, \([ud]\) represents wave functions with a \( u, d \) quark pair that is anti-symmetric in spin and flavor. These diquarks are often called good diquarks. The presence of good diquarks leads to a stronger binding. In the 4-plet, all three quark pairs have such a component w.r.t. their exchange. We denote this by \([ud,us,ds]\). Thus there are three good diquarks in the wave function. This fact leads to the low masses of the 4-plet members. The similarity of the mass splittings supports similar interpretations of the four resonances from \( \Lambda(1520) \) to \( \Xi_b \).

In most publications, both resonances, \( A_c(2595)1/2^- \) and \( A_c(2625)3/2^- \), are discussed as 3-quark baryons. However, Nieves and Pavao \cite{27} have studied these two resonances in an effective field theory that incorporates the interplay between \( \Sigma_c^+ \pi - N D^* \) baryon-meson dynamics and bare P-wave \( cuds \) quark-model state and suggest that these two resonances are not heavy quark symmetry spin partners. Instead, they see \( A_c(2625)3/2^- \) as a dressed three-quark state while \( A_c(2595)1/2^- \) is reported to have a predominant molecular structure. Nevertheless, the two states \( A_c(2625)3/2^- \) and \( A_c(2595)1/2^- \) obviously form a spin doublet.

The mass shift in \( H \) atoms between the two ground states with electron and proton spins parallel or antiparallel is called hyperfine splitting. We borrow this expression to discuss the difference between the ground states with all three quark spins adding to \( J = 3/2 \) (belonging to the symmetric 20-plet) and those having \( J = 1/2 \) (that belong to the mixed-symmetry 20-plet). We thus compare masses of the fully symmetric 20-plet with those from the 3-plet or 6-plet within the \( 20_m \)-plet (see Table 6). The two configurations differ by the orientation of the heavy-quark spin relative to the spin of the light diquark. According to the heavy-quark-spin symmetry, this mass difference has to vanish with \( m_Q \rightarrow \infty \). In the Table we assume constituent quark masses of 0.15 GeV \((u,d)\), 0.3 GeV \((s)\), 1.25 GeV \((c)\) and 4.1 GeV \((b)\). The \( J^P = 3/2^- \) states have a fully symmetric flavor wave function, the \( J^P = 1/2^+ \) states have an antisymmetric quark pair (a good diquark) that is indicated in

### Table 4. Increase of baryon masses with the number of strange quarks.

|          | \( n \rightarrow s \) | \( 2n \rightarrow 2s \) | \( 3n \rightarrow 3s \) |
|----------|------------------------|-------------------------|-------------------------|
| \( \Delta^- (1232)3/2^+ \) | \( \Sigma^- (1385)3/2^+ \) | \( \Xi^- (1530)3/2^+ \) | \( \Omega^- 3/2^+ \) |
| \( +155 \text{ MeV} \)      | \( +148 \text{ MeV} \)    | \( +137 \text{ MeV} \)    |                        |
| \( \Sigma(2520)3/2^+ \)     | \( \Sigma(2645)3/2^+ \)   | \( \Omega(2770)3/2^+ \)   |                        |
| \( +128 \text{ MeV} \)      | \( +120 \text{ MeV} \)    |                          |                        |
| \( \Sigma(2555)1/2^+ \)     | \( \Sigma(2625)1/2^+ \)   | \( \Omega(2710)1/2^+ \)   |                        |
| \( +121 \text{ MeV} \)      | \( +116 \text{ MeV} \)    |                          |                        |
| \( \Sigma(5816)1/2^+ \)     | \( \Xi(6030)1/2^+ \)      | \( \Omega(6276)1/2^+ \)   |                        |
| \( +120 \text{ MeV} \)      | \( +111 \text{ MeV} \)    |                          |                        |

### Table 5. Mass splitting between baryon ground states belonging to the symmetric 20plet (with \( J^P = 3/2^- \)) and to the mixed-symmetry 20plet (with \( J^P = 1/2^+ \)).

|          | \( \Sigma_b 3/2^- \) | \( \Xi_b 3/2^- \) | \( \Delta_b 3/2^- \) | \( \Xi_b 3/2^- \) |
|----------|-----------------|-----------------|-----------------|-----------------|
| \( [us,ub,db] \) | \( [us,ub,ab] \) | \( [us,ub,bd] \) | \( [us,uc,bc] \) |
| \( \delta M = 310 \text{ MeV} \) | \( \delta M = 300 \text{ MeV} \) | \( \delta M = 350 \text{ MeV} \) | \( \delta M = 400 \text{ MeV} \) |
In heavy-quark baryons, the two oscillators decouple, and \( \Lambda \)\(^2 \). Yet, the mass of \( \Lambda \)\(^5 \) MeV above the \( \Lambda \)\(^3 \) excitation, the other five expected states are excited in the \( \Lambda \)\(^3 \) parity states with \( s \)\(^2 \). In light-baryon spectroscopy, there are seven negative-parity \( A \) states expected in the first excitation level: two singlet states with \( J^P = 1/2^-, 3/2^- \), two octet states with intrinsic total quark spin \( s = 1/2 \) and \( J^P = 1/2^-, 3/2^- \), and a \( J^P = 1/2^-, 3/2^-, 5/2^- \) triplet with \( s = 3/2 \). In light baryons, both \( \lambda \) and \( \rho \) oscillator are coherently excited. In heavy-quark baryons, the two oscillators decouple, and the \( \lambda \) and \( \rho \) modes are well separated. The low-lying spin-doublet of \( P \)-wave \( \Lambda \) states is dominated by a \( \lambda \)-mode excitation, the other five expected states are excited in the \( \rho \) mode.

Unfortunately, only one negative-parity state at a higher mass has been reported, the \( \Lambda_c(2940)3/2^- \). Its mass is 653 MeV above the \( \Lambda_c^+ \). We interpret this state as \( I_P \) excitation with a diquark spin \( s = 1 \). The \( \Lambda(1690)3/2^- \) is only 570 MeV above the \( \Lambda_c \), it is excited in both the \( \lambda \) and \( \rho \) mode.

The mass of \( \Lambda_c(2940)3/2^- \) (with intrinsic orbital angular momentum \( L = 1 \)) is above the masses of the positive-parity states \( \Lambda_c(2860)3/2^+ \) and \( \Lambda_c(2880)5/2^+ \) (having \( L = 2 \)). Yet, the mass of \( \Lambda(1690)3/2^- \) falls well below the masses of \( \Lambda(1890)3/2^+ \) and \( \Lambda(1820)5/2^+ \) for reasons discussed above.

### 8 Pentaquarks

In 2015, the LHCb collaboration reported the observation of two exotic structures in the \( J/\psi p \) system, a broad resonant structure with a Breit-Wigner width of about 200 MeV called \( P_c(4380)^+ \) and a narrow state, \( P_c(4450)^+ \). The exotic structures were observed in the reaction \( \Lambda_b^0 \rightarrow J/\psi K^- p \). An excited three-quark nucleon cannot decay into \( J/\psi p \), this would violate the OZI rule. Hence the minimal quark content is (ccuud). The findings met with great interest; the publication is quoted nearly 1500 times (2022, November). Indeed narrow baryonic resonances with hidden charm had been predicted several years before as dynamically generated states.

A multitude of different interpretations of the observed structures is offered in the literature, but none is accepted anonymously. There are numerous reviews on tetra- and pentaquarks and their possible interpretations.

With increased statistics, \( P_c(4312)^+ \) was confirmed and the higher-mass \( P_c(4450)^+ \) was shown to be split into two narrow overlapping structures, \( P_c(4440)^+ \) and \( P_c(4457)^+ \). The existence of the broad resonance was not confirmed. The data and a fit are shown in Fig. 7, which also displays some relevant thresholds. In addition, a further smaller structure can be seen at 4380 MeV, close to the \( \Sigma_c^+ D^0 \) threshold. A narrow structure here is expected in molecular models (see e.g. [37]), but due to limited statistics there was no attempt to describe it in the recent LHCb analysis.

Quantum numbers \( J^P = 3/2^- \) and \( 5/2^+ \) were preferred for \( P_c(4380)^+ \) and \( P_c(4450)^+ \). In the later publication, no quantum numbers are determined.

In the reaction \( B_s^0 \rightarrow J/\psi p p \) a pentaquark-like structure, named \( P_c(4337)^+ \), was observed in the \( J/\psi p \) and \( J/\psi p \) mass distributions. The significance, as determined from a 3-body amplitude analysis, is between 3.1 and 3.7 \( \sigma \). Its Breit-Wigner parameters are incompatible with the structures observed in \( \Lambda_b \) decays. The lighter state at 4312 MeV was not found in this reaction, highlighting the importance of the production mechanism for the formation of these resonances. However, it has been pointed out that in a region with many close-by
thresholds, the Breit-Wigner parameters measured in a particular channel may differ significantly from the pole location.

Strange counterparts to these pentaquark states have been searched for by LHCb in the reaction $\Xi^{-}_b \rightarrow J/\psi AK^-$. Resonances in the $J/\psi A$ system are denoted by $P^0_{cs}(4312)$ and have (ccuds) as minimal quark content. A peak was found close to the $\Xi^0_b D^{*0}$ threshold with a mass and width given in Table 7.

The $J/\psi A$ system was also investigated in 2019 by CMS, exploiting the small phase space available in the B-meson decay $B^- \rightarrow J/\psi A p$. The analysis showed that the observed spectrum was incompatible with a pure phase space distribution. Very recently, the LHCb collaboration reported a new analysis of this process. Now, a signal in the $J/\psi A$ subsystem, with preferred quantum numbers $J^P = 1/2^-$, was established at high significance, named $P^0_{cs}(4338)$. Due to the presence of the second (anti)baryon, the phase space in the $B$-meson decay is too small to access the heavier pentaquark state found in the $\Xi_b$ decay.

These structures have stimulated an intense discussion of the nature of these structures. Do they originate from threshold singularities due to rescattering in the final state leading to a logarithmic branching point in the amplitude? Are they hadronic molecules like the deuteron? Are they compact or triple-quark–diquark systems or states where a $cc$ center is surrounded by light quarks?

The peaks are mostly seen very close to important thresholds. Thus they could originate from threshold singularities. We refer to a few publications. The LHCb collaboration studied this hypothesis and found it incompatible with the data, but the attempts continued.

### Table 7. $J/\psi$ resonances found by the LHCb collaboration.

| $P_c(4312)^+$ | $M = (4311.9 \pm 0.7^{+0.8}_{-0.6}$ | MeV |
| $Γ = (9.8 \pm 2.3^{+1.7}_{-1.5}$ | MeV |
| $P_c(4380)^+$ | $M = (4380 \pm 30$ | MeV |
| $Γ = (205 \pm 90$ | MeV |
| $P_c(4440)^+$ | $M = (4440.3 \pm 1.3^{+1.4}_{-1.2}$ | MeV |
| $Γ = (20.6 \pm 4.9^{+5.7}_{-10.1}$ | MeV |
| $P_c(4457)^+$ | $M = (4457.3 \pm 0.6^{+1.2}_{-1.1}$ | MeV |
| $Γ = (6.4^{+2.0}_{-1.7}$ | MeV |
| $P_c(4337)^+$ | $M = (4337^{+7.2}_{-7.2}$ | MeV |
| $Γ = (29^{+26}_{-12.1}$ | MeV |

### Table 8. $J/\psi A$ pentaquarks.

| $P_{cs}^{0}(4459)$ | $M = (4588.8 \pm 2.9^{+1.1}_{-1.2}$ | MeV |
| $Γ = (17.3 \pm 6.5^{+5.9}_{-5.7}$ | MeV |
| $P_{cs}^{0}(4338)$ | $M = (4332.8 \pm 0.7^{+0.8}_{-0.4}$ | MeV |
| $Γ = (7.0 \pm 1.2^{+1.3}_{-1.2}$ | MeV |

Very popular are interpretations as bound states composed of charmed baryons and anti-charmed mesons or of charmonium states binding light-quark baryons. The pentaquark states are then seen to be of molecular nature and be bound by coupled-channel dynamics. Diquark-triquark models were studied, and sum rules are exploited in Refs. 67, 68.

### 9 Concluding remarks:

The study of hadrons with heavy quarks has developed into a fascinating new field of particle physics. Particular excitement is due to the discovery of unconventional structures that are hotly debated. But also the “regular” heavy hadrons yield very useful information on the interactions of quarks in the confinement region.

### References:

1. R. L. Workman et al., “Review of Particle Physics,” PTEP, vol. 2022, p. 083C01, 2022.
2. R. Aaij et al., “Observation of $J/\psi$ Resonances Consistent with Pentaquark States in $A^0_c \rightarrow J/\psi K^- p$ Decays,” Phys. Rev. Lett., vol. 115, p. 072001, 2015.
3. R. Aaij et al., “Observation of a narrow pentaquark state, $P_c(4312)^+$, and of two-peak structure of the $P_c(4450)^+$,” Phys. Rev. Lett., vol. 122, no. 22, p. 222001, 2019.
4. J. Gratrex, B. Melić, and I. Nišandžić, “Lifetimes of singly charmed hadrons,” 2022.
5. M. Mattsson et al., “First Observation of the Doubly Charmed Baryon $\Xi_{cc}^{++}$,” Phys. Rev. Lett., vol. 89, p. 112001, 2002.
6. A. Ocherashvili et al., “Confirmation of the double charm baryon $\Xi^{++}(cc)(3520)$ via its decay to $pD^0 K^-$,” Phys. Lett. B, vol. 628, pp. 18–24, 2005.
7. R. Aaij et al., “Precision measurement of the $\Xi^{++}_{cc}$ mass,” JHEP, vol. 02, p. 049, 2020.
8. R. Aaij et al., “Search for the doubly charmed baryon $\Xi_c^{++}$ in the $\Xi^0_c \pi^- \pi^+$ final state,” JHEP, vol. 12, p. 107, 2021.
9. R. Aaij et al., “Search for the doubly heavy baryon $\Xi_{cc}^{++}$ decaying to $J/\psi$ $\Xi^{++}$,” 4 2022.
10. B. Aubert et al., “Observation of an excited charm baryon $\Omega_c^*$ decaying to $\Lambda_c^0 \gamma$,” Phys. Rev. Lett., vol. 97, p. 232001, 2006.
11. T. J. Moon et al., “First determination of the spin and parity of the charmed-strange baryon $\Xi_c(2970)^+$,” Phys. Rev. D, vol. 103, no. 11, p. L111101, 2021.
12. R. Aaij et al., “First observation of excited $\Omega_c^*$ states,” Phys. Rev. Lett., vol. 124, no. 8, p. 082002, 2020.
13. S. Capstick and N. Isgur, “Baryons in a relativized quark model with chromodynamics,” Phys. Rev. D, vol. 34, no. 9, pp. 2809–2835, 1986.
14. H.-X. Chen, W. Chen, X. Liu, Y.-R. Liu, and S.-L. Zhu, “A review of the open charm and open bottom systems,” Rept. Prog. Phys., vol. 80, no. 7, p. 076201, 2017.
15. D. Ebert, R. N. Faustov, and V. O. Galkin, “Spectroscopy and Regge trajectories of heavy baryons in the relativistic quark-diquark picture,” Phys. Rev. D, vol. 84, p. 014025, 2011.
16. G.-L. Yu, Z.-Y. Li, Z.-G. Wang, J. Lu, and M. Yan, “Systematic analysis of single heavy baryons $\Lambda_Q$, $\Sigma_Q$ and $\Omega_Q$,” 6 2022.

17. Z.-Y. Li, G.-L. Yu, Z.-G. Wang, J. Lu, and J.-Z. Gu, “Systematic analysis of strange single heavy baryons,” 7 2022.

18. S. Migura, D. Merten, B. Metsch, and H.-R. Petry, “Semileptonic decays of baryons in a relativistic quark model,” Eur. Phys. J. A, vol. 28, p. 55, 2006.

19. A. Vakearce, H. Garcilazo, and J. Vijande, “Heavy baryon spectroscopy with relativistic kinematics,” Phys. Lett. B, vol. 733, pp. 288–295, 2014.

20. B. Chen, K.-W. Wei, and A. Zhang, “Assignments of $\Lambda_Q$ and $\Sigma_Q$ baryons in the heavy quark-light diquark picture,” Eur. Phys. J. A, vol. 51, p. 82, 2015.

21. R. N. Faustov and V. O. Galkin, “Heavy Baryon Spectrum in the Relativistic Quark Model,” Particles, vol. 3, no. 1, pp. 234–244, 2020.

22. R. Aaij et al., “Observation of five new narrow $\Omega^0_c$ states decaying to $\Xi_c^+ K^-$,” Phys. Rev. D, vol. 101, no. 1, p. 014018, 2020.

23. J. Yelton et al., “Observation of excited $\Omega_c$ Charged Baryons in $e^+e^-$ Collisions,” Phys. Rev. D, vol. 97, no. 5, p. 051102, 2018.

24. Y. Kim, Y.-R. Liu, M. Oka, and K. Suzuki, “Heavy baryon spectrum with chiral multiplets of scalar and vector diquarks,” Phys. Rev. D, vol. 104, no. 5, p. 054012, 2021.

25. H.-M. Yang, H.-X. Chen, E.-L. Cui, A. Hosaka, and Q. Mao, “Decay properties of $P$-wave bottom baryons within light-cone sum rules,” Eur. Phys. J. C, vol. 80, no. 2, p. 80, 2020.

26. H. Bahtiyar, K. U. Can, G. Erkol, P. Gubler, M. Oka, and T. T. Takahashi, “Charged baryon spectrum from lattice QCD near the physical point,” Phys. Rev. D, vol. 102, no. 5, p. 054513, 2020.

27. J. Nieves and R. Pavao, “Nature of the lowest-lying odd parity charged baryon $\Lambda_c(2595)$ and $\Lambda_c(2625)$ resonances,” Phys. Rev. D, vol. 101, no. 1, p. 014018, 2020.

28. J. Hofmann and U.-G. Meißner, “D-wave baryon resonances with charm from coupled-channel dynamics,” Nucl. Phys. A, vol. 776, pp. 17–51, 2006.

29. J. Wu, R. Molina, E. Oset, and B. S. Zou, “Dynamically generated $N^*$ and $A^*$ resonances in the hidden charm sector around 4.3 GeV,” Phys. Rev. C, vol. 84, p. 015202, 2011.

30. J.-J. Wu, T. S. H. Lee, and B. S. Zou, “Nucleon Resonances with Hidden Charm in Coupled-Channel Models,” Phys. Rev. C, vol. 85, p. 044002, 2012.

31. J.-Y. Chen, W. Chen, X. Liu, and S.-L. Zhu, “The hidden-charm pentaquark and tetraquark states,” Phys. Rept., vol. 639, pp. 1–121, 2016.

32. F.-K. Guo, C. Hanhart, U.-G. Meißner, Q. Wang, Q. Zhao, and B.-S. Zou, “Hadronic molecules,” Rev. Mod. Phys., vol. 90, no. 1, p. 015004, 2018. [Erratum: Rev.Mod.Phys. 94, 029901 (2022)].

33. S. L. Olsen, T. Skwarnicki, and D. Zieminska, “Nonstandard heavy mesons and baryons: Experimental evidence,” Rev. Mod. Phys., vol. 90, no. 1, p. 015003, 2018.

34. N. Brambilla, S. Eidelman, C. Hanhart, A. Nefediev, C.-P. Shen, C. E. Thomas, A. Vairo, and C.-Z. Yuan, “The X(3872) states: experimental and theoretical status and perspectives,” Phys. Rept., vol. 873, pp. 1–154, 2020.

35. Y.-R. Liu, H.-X. Chen, W. Chen, X. Liu, and S.-L. Zhu, “Pentaquark and Tetraquark states,” Prog. Part. Nucl. Phys., vol. 107, pp. 237–320, 2019.
55. H. Xu, Q. Li, C.-H. Chang, and G.-L. Wang, “Recently observed $P_c$ as molecular states and possible mixture of $P_c(4457)$,” *Phys. Rev. D*, vol. 101, no. 5, p. 054037, 2020.

56. R. Chen, “Can the newly reported $P_{cs}(4459)$ be a strange hidden-charm $\Xi_c D^*$ molecular pentaquark?,” *Phys. Rev. D*, vol. 103, no. 5, p. 054007, 2021.

57. H.-X. Chen, W. Chen, X. Liu, and X.-H. Liu, “Establishing the first hidden-charm pentaquark with strangeness,” *Eur. Phys. J. C*, vol. 81, no. 5, p. 409, 2021.

58. Q. Wu, D.-Y. Chen, and R. Ji, “Production of $P_{cs}(4459)$ from $\Xi_b$ Decay,” *Chin. Phys. Lett.*, vol. 38, no. 7, p. 071301, 2021.

59. J.-X. Lu, M.-Z. Liu, R.-X. Shi, and L.-S. Geng, “Understanding $P_{cs}(4459)$ as a hadronic molecule in the $\Xi_c^- \rightarrow J/\psi AK^-$ decay,” *Phys. Rev. D*, vol. 104, no. 3, p. 034022, 2021.

60. B. B. Malabarba, K. P. Khemchandani, and A. M. Torres, “$N$ states with hidden charm and a three-body nature,” *Eur. Phys. J. A*, vol. 58, no. 2, p. 33, 2022.

61. N. Yalikun, Y.-H. Lin, F.-K. Guo, Y. Kamiya, and B.-S. Zou, “Coupled-channel effects of the $\Sigma_c^* D^*-\Lambda(2595) D^-$ system and molecular nature of the $P_c$ pentaquark states from one-boson exchange model,” *Phys. Rev. D*, vol. 104, no. 9, p. 094039, 2021.

62. R. Zhu and C.-F. Qiao, “Pentaquark states in a diquark-triquark model,” *Phys. Lett. B*, vol. 756, pp. 259–264, 2016.

63. A. Ali and A. Y. Parkhomenko, “Interpretation of the narrow $J/\psi p$ Peaks in $\Lambda_c \rightarrow J/\psi pK^-$ decay in the compact diquark model,” *Phys. Lett. B*, vol. 793, pp. 365–371, 2019.

64. K. Azizi, Y. Sarac, and H. Sundu, “Investigation of $P_{cs}(4459)^0$ pentaquark via its strong decay to $AJ/\Psi_c$,” *Phys. Rev. D*, vol. 103, no. 9, p. 094033, 2021.

65. Z.-G. Wang, “Analysis of the $P_c(4312), P_c(4440), P_c(4457)$ and related hidden-charm pentaquark states with QCD sum rules,” *Int. J. Mod. Phys. A*, vol. 35, no. 01, p. 2050003, 2020.

66. Z.-G. Wang, “Analysis of the $P_{cs}(4459)$ as the hidden-charm pentaquark state with QCD sum rules,” *Int. J. Mod. Phys. A*, vol. 36, no. 10, p. 2150071, 2021.