84. Charmed Baryons

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84.1 Spectrum

Similar to the light baryons, the naming convention for charmed baryon base symbols is determined by their isospin, I, and charm-strangeness, $C+S$, quantum numbers: In particular, Λ_c, Σ_c, $\Xi_{c,cc}$ and $\Omega_{c,cc,ccc}$ with $I(C+S) = 0(1)$, $1(1)$, $1/2(2)$ and $0(3)$, respectively. While this review considers only the charmed baryons, approximate heavy quark flavor symmetry implies the spectroscopy of the bottom baryons is expected to be similar, up to corrections of order $\Lambda_{\rm QCD}/m_{c,b}$.

Figure 84.1(a) shows the spectrum of the singly-charmed baryons: There are now 36 such established states. In the quark model picture (see the *Quark Model* review), states consistent with all singly-charmed ground-state (zero angular momentum, or S-wave, state) baryons have been discovered, along with many excited states. The $\Lambda_c(2860)$ and the five heaviest Ω_c^0's are recent, intriguing discoveries. The spin-parity quantum numbers of the latter are currently unknown, but one may speculate they correspond to the five ssc excited baryons in a P-wave state, although other interpretations are also possible and plausible.

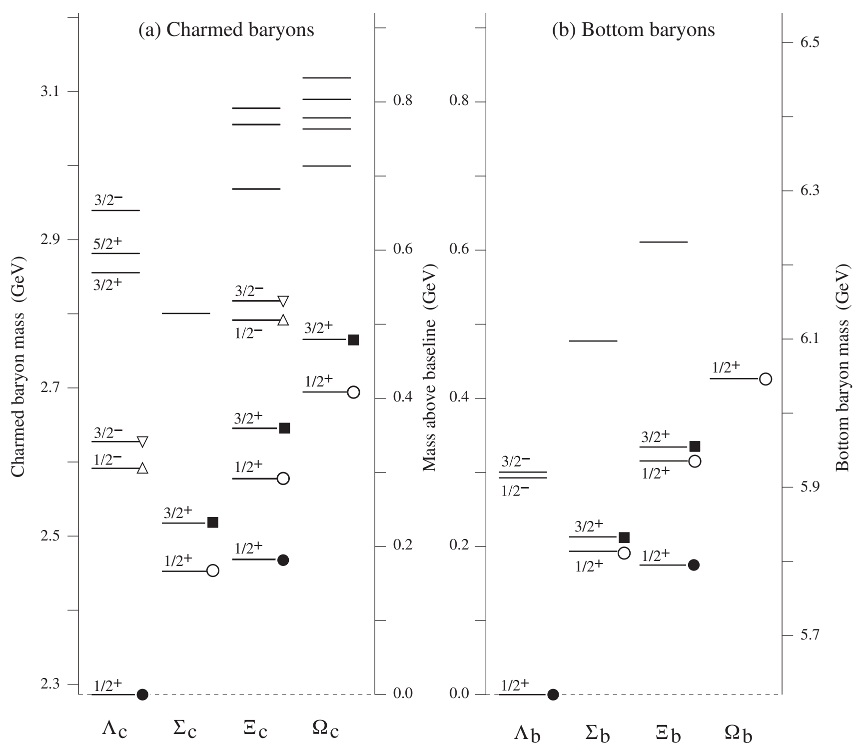

Figure 84.1: (a) The spectrum of established singly-charmed baryons, with their J^P assignments (where known). In accordance with their isospin, the Σ_c (Ξ_c) lines each correspond to three (two) charged or neutral states that are nearly degenerate, with the exception of the upper two Ξ_c lines for which only the charged state has been found. Unique flavor $SU(3)$ representations are shown by various filled and open symbols: The three $J^P = 3/2^+$ ($J^P = 1/2^+$) lines marked with a filled square (open circle) fill a ground-state **6** of flavor $SU(3)$; the two $J^P = 1/2^+$ ($1/2^-$ and $3/2^-$) lines marked by a filled circle (open triangles) fill a ground-state (excited-state) $\bar{\mathbf{3}}$. Fig 84.1(b) shows a similar spectrum for several known bottom baryons.

84.2 Flavor symmetry

Just as for the light mesons and baryons, approximate flavor $SU(3)$ symmetry of the light quarks – the u, d, and s – is expected to relate matrix elements of charmed baryons belonging to the same multiplet, up to corrections of order $(m_s - m_d)/\Lambda_{\rm QCD} \sim 20\%$. (Similarly, isospin relations should hold to the percent level.) This includes Gell-Mann-Okubo mass relations – a set of linear combinations of masses that must vanish up to higher-order $SU(3)$-breaking corrections – as well as similar relations between matrix elements for charmed baryon multibody decays. These relations may be constructed order-by-order in the appropriate symmetry-breaking parameters.

For singly-charmed baryons with valence quarks $q_1 q_2 c$, the flavor $SU(3)$ tensor product of the two light quarks $\mathbf{3} \times \mathbf{3} = \mathbf{6} + \bar{\mathbf{3}}$. For ground-state baryons, the overall antisymmetry of baryon wavefunction requires the light diquark to either form a spin-0 color antitriplet, antisymmetric under the interchange of the two light quark flavors – i.e. the $\bar{\mathbf{3}}$ – or a spin-1 color antitriplet that is symmetric under this interchange – i.e. the $\mathbf{6}$. The spin-0 $\bar{\mathbf{3}}$ can only combine with the charm quark to form $J^P = 1/2^+$ states, while the spin-1 $\mathbf{6}$ can combine to form states either $J^P = 1/2^+$ or $J^P = 3/2^+$. States consistent with the corresponding $\bar{\mathbf{3}}$ and two $\mathbf{6}$ $SU(3)$ representations are denoted in Figure 84.1 by filled circles, open circles and filled squares, respectively. In Fig. 84.2 we show the explicit contents of the $\bar{\mathbf{3}}$ and $\mathbf{6}$ ground-state representations. The singly-charmed baryons within each multiplet obey isospin and $SU(3)$ mass relations at the expected orders.

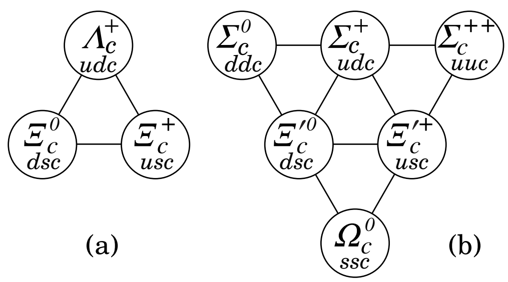

Figure 84.2: The SU(3) $\bar{\mathbf{3}}$ (a) and $\mathbf{6}$ (b) ground-state $J^P = 1/2^+$ representations. The $\mathbf{6}$ ground-state with $J^P = 3/2^+$ is identical in structure to the right-hand figure.

Excited singly-charmed baryon states may arise as higher orbital angular momentum states. For instance, for such a baryon in a P-wave state, the allowed spin-flavor representations for the light diquark are either a spin-1 $\bar{\mathbf{3}}$ or a spin-0 $\mathbf{6}$. Combined with the charm quark, the $\bar{\mathbf{3}}$ can then generate $J^P = 1/2^-$, $3/2^-$ or $5/2^-$ states: States consistent with the $1/2^-$ and $3/2^-$ $\bar{\mathbf{3}}$ representations are indicated in Figure 84.1 by open triangles. (One might speculate that the $J^P = 5/2^-$ $\bar{\mathbf{3}}$ could be composed of the claimed $\Lambda_c(2765)$ – not shown in the figure – and the $\Xi_c(2930)$.) Note that excited states might also arise from hadronic 'molecule' or pentaquark type states, $\sim qqq\bar{q}c$, which may generate baryons in higher $SU(3)$ representations.

To extend this discussion to doubly or triply charmed baryons, or charmless baryons, it is convenient to embed the baryons into flavor $SU(4)$, in which u, d, s and c transform as a $\mathbf{4}$. Flavor $SU(4)$ is heavily broken, and is not a good approximate symmetry of QCD. However, under the decomposition $SU(4) \to SU(3) \times U(1)_{\rm charm}$, it does provide a useful bookkeeping scheme for the various flavor $SU(3)$ multiplets with different numbers of valence charm quarks.

For instance, for charmed baryons with three quarks, the tensor product $\mathbf{4}\times\mathbf{4}\times\mathbf{4} = \mathbf{20}_S + \mathbf{20}_M + \mathbf{20}_M + \bar{\mathbf{4}}$.[1] The spin-flavor representation of a ground-state baryon must be fully symmetric, so that ground-state baryons may belong to the $\mathbf{20}_S$ and a single combination of the two $\mathbf{20}_M$'s, with

[1] More generally, for $SU(N)$, $N \times N \times N = [N(N+1)(N+2)/6] + 2 \times [N(N^2-1)/3] + [N(N-1)(N-2)/6]$. The $\mathbf{20}_S$, $\mathbf{20}_M$ and $\bar{\mathbf{4}}$ correspond to the representations with Dynkin labels $(3,0,0)$, $(1,1,0)$ and $(0,0,1)$, respectively. See Ref. [1] for a review.

spin and parity $J^P = 3/2^+$ and $J^P = 1/2^+$, respectively. The $\bar{\mathbf{4}}$, however, is fully antisymmetric in flavor indices, and one cannot form the required fully antisymmetrized spin state from three quarks each with two possible spin configurations. This can be also understood directly in terms of the $SU(8)$ contracted spin-flavor group: The only fully symmetric irreducible representation contained in $\mathbf{8}\times\mathbf{8}\times\mathbf{8}$ is the $\mathbf{120}$, which contains a $(\mathbf{20}_S, \mathbf{4})$ and a $(\mathbf{20}_M, \mathbf{2})$ with respect to $SU(4)\times SU(2)_{\rm spin}$.

The decompositions $\mathbf{20}_S \to \mathbf{10}_0 + \mathbf{6}_1 + \bar{\mathbf{3}}_2 + \mathbf{1}_3$ and $\mathbf{20}_M \to \mathbf{8}_0 + \mathbf{6}_1 + \bar{\mathbf{3}}_1 + \mathbf{3}_2$, where the subscript indicates charm number, indicates the expected flavor $SU(3)$ multiplets for each value of charm number in the ground-state baryons. Fig. 84.3(a) shows the $\mathbf{20}_S$ representation, in which each charm number layer in the decomposition to $SU(3)\times U(1)_{\rm charm}$ is shaded in yellow. The bottom $c = 0$ level is the $J^P = 3/2^+$ flavor $SU(3)$ baryon decuplet containing the $\Delta(1232)$. Fig. 84.3(b) shows the $\mathbf{20}_M$ representation, whose bottom $c = 0$ level is the $1/2^+$ $SU(3)$ light baryon octet, containing the nucleons.

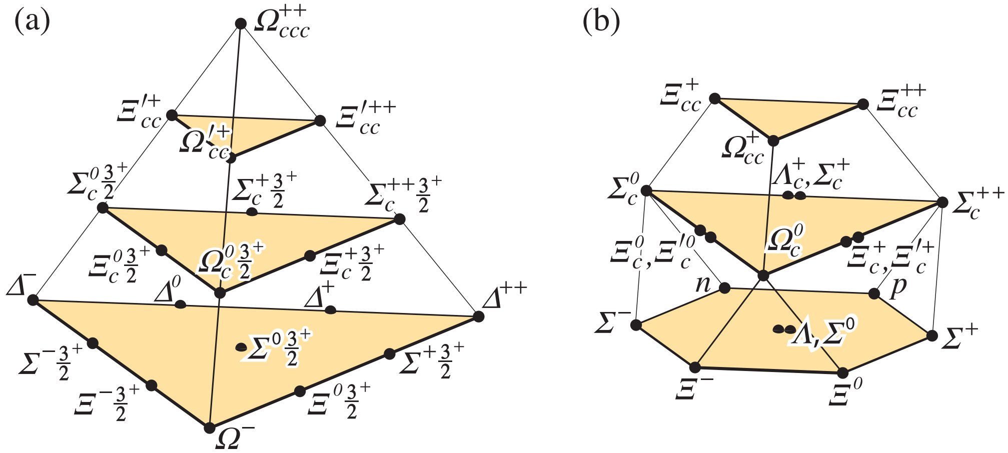

Figure 84.3: (a) The $J^P = 3/2^+$ flavor $SU(4)$ ground-state charmed baryons in the $\mathbf{20}_S$, with the flavor $SU(3)$ baryon decuplet on the lowest level. (b) The $J^P = 1/2^+$ ground-state charmed baryons in the $\mathbf{20}_M$-plet with the flavor $SU(3)$ baryon octet on the lowest level. In some conventions, the states with a "$\frac{3}{2}^+$" label are instead denoted with a * superscript to distinguish them from the $J^P = 1/2^+$ states.

Of the doubly charmed baryons, only the Ξ_{cc}^{++} has been discovered, though its spin-parity is unknown. For excited baryons in, e.g., a P-wave state, the same contracted spin-flavor analysis implies that there are excited baryon states in, e.g., a $\mathbf{20}_M$ with $J^P = 1/2^-$ or a $\bar{\mathbf{4}}$ with $J^P = 3/2^-$, which together fill the fully antisymmetric $\mathbf{56}$ of $SU(8)$. The $\bar{\mathbf{4}}$ decomposes into $\bar{\mathbf{3}}_1 + \mathbf{1}_0$, consistent with the $3/2^-$ singly-charmed $\bar{\mathbf{3}}$'s denoted by open triangles in Fig. 84.1(a). Just as for flavor $SU(3)$, excited state $\mathbf{20}_{S,M}$ and $\bar{\mathbf{4}}$ representations may also arise with other spin-parity assignments, and higher representations may also be present.

References

[1] R. Slansky, Phys. Rept. **79**, 1 (1981).