

## CHARMED BARYONS

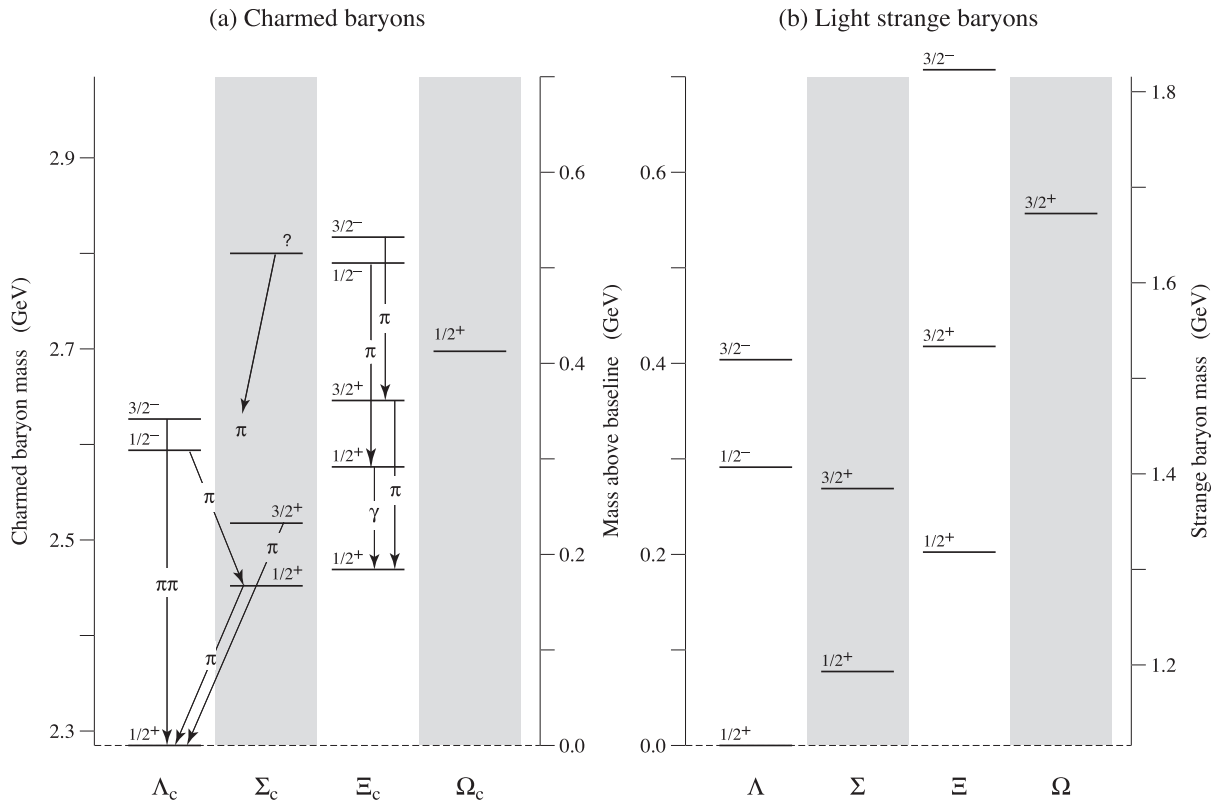
Revised February 2006 by C.G. Wohl (LBNL).

There have been twelve papers on charmed baryons since our 2004 *Review*. Probably the most important results are (1) the discovery of another  $\Sigma_c$ , at 2800 MeV, by the BELLE experiment, and (2) a very precise measurement of the  $\Lambda_c^+$  mass by the BABAR experiment. This mass is 1.56 MeV and 2.6 (old) standard deviations higher than our 2004 value. We use the new measurement as our  $\Lambda_c^+$  mass, and this increases all the other  $\Lambda_c^+$  masses, as well as all  $\Sigma_c$  masses, a like amount.

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There are twelve known charmed baryons, each with one  $c$  quark.\* Fig. 1(a) shows the mass spectrum, and for comparison Fig. 1(b) shows the spectrum of the lightest strange baryons. The  $\Lambda_c$  and  $\Sigma_c$  spectra ought to look much like the  $\Lambda$  and  $\Sigma$  spectra, since a  $\Lambda_c$  or a  $\Sigma_c$  is obtained from a  $\Lambda$  or a  $\Sigma$  by changing the  $s$  quark to a  $c$  quark. However, a  $\Xi$  or an  $\Omega$  has more than one  $s$  quark, only *one* of which is changed to a  $c$  quark to make a  $\Xi_c$  or an  $\Omega_c$ . Thus the  $\Xi_c$  and  $\Omega_c$  spectra ought to be richer than the  $\Xi$  or  $\Omega$  spectra.\*\*

Before discussing the observed spectra, we review the theory of SU(4) multiplets, which tells us what charmed baryons we should expect to find; this is essential, because the spin-parity values given in Fig. 1(a) have not been measured but have been assigned in accord with expectations of the theory.

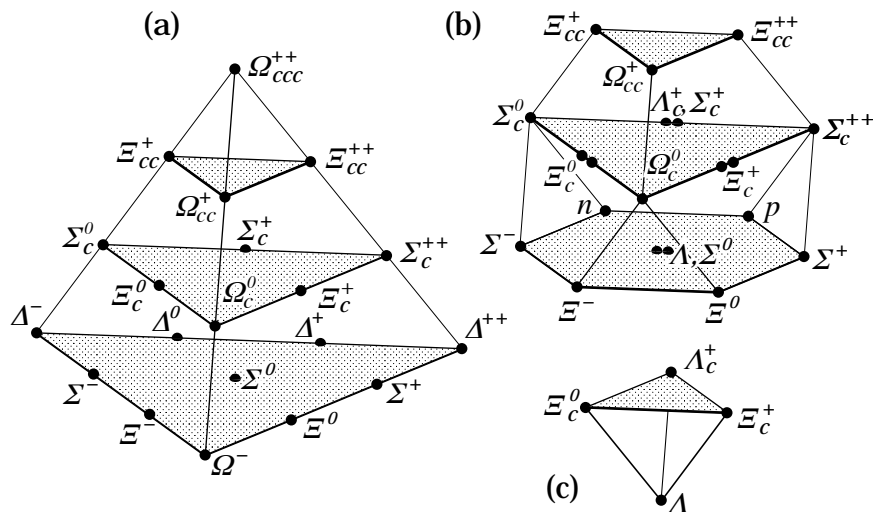


**Fig. 1.** (a) The known charmed baryons, and (b) the lightest strange baryons. Isospin splittings are not shown, and the only transitions shown are those between the charmed baryons. Note that there are two  $J^P = 1/2^+$   $\Xi_c$  states, and that the  $\Omega_c$  does not have  $J = 3/2$ . Actually, none of the  $J^P$  values of the charmed baryons has been measured (except perhaps for the  $1/2^+\Lambda_c$ ), but they are all very likely as shown—see the discussion.

***SU(4) multiplets***—Baryons made from  $u$ ,  $d$ ,  $s$ , and  $c$  quarks belong to  $SU(4)$  multiplets. The multiplet numerology, analogous to  $3 \times 3 \times 3 = 10 + 8_1 + 8_2 + 1$  for the subset of baryons made from just  $u$ ,  $d$ , and  $s$  quarks, is  $4 \times 4 \times 4 = 20 + 20'_1 + 20'_2 + \bar{4}$ . Figure 2(a) shows the 20-plet whose bottom level is an  $SU(3)$  decuplet, such as the decuplet that includes the  $\Delta(1232)$ . Figure 2(b) shows the  $20'$ -plet whose bottom level is an  $SU(3)$  octet, such as the octet that includes the nucleon. Figure 2(c) shows the  $\bar{4}$  multiplet, an inverted tetrahedron. One level up in each multiplet are the baryons with one  $c$  quark. All the

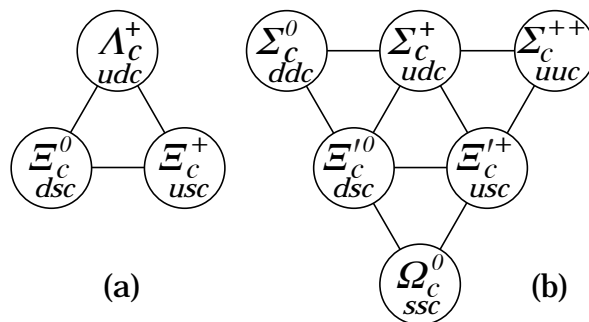
baryons in a given multiplet have the same spin and parity. Each  $N$  or  $\Delta$  or  $SU(3)$ -singlet- $\Lambda$  resonance calls for another  $20'$ - or  $20$ - or  $\bar{4}$ -plet, respectively.

The flavor symmetries shown in Fig. 2 are of course very badly broken, but the figure is the simplest way to see what charmed baryons should exist. For example, from Fig. 2(b), we expect to find, in the same  $J^P = 1/2^+$   $20'$ -plet as the nucleon, a  $\Lambda_c$ , a  $\Sigma_c$ , two  $\Xi_c$ 's, and an  $\Omega_c$ . Note that this  $\Omega_c$  is not in the same  $SU(4)$  multiplet as the famous  $J^P = 3/2^+$   $\Omega^-$ .



**Figure 2:**  $SU(4)$  multiplets of baryons made of  $u$ ,  $d$ ,  $s$ , and  $c$  quarks. (a) The  $20$ -plet with an  $SU(3)$  decuplet on the lowest level. (b) The  $20'$ -plet with an  $SU(3)$  octet on the lowest level. (c) The  $\bar{4}$ -plet.

Figure 3 shows in more detail the middle level of the  $20'$ -plet of Fig. 2(b); it splits apart into two  $SU(3)$  multiplets, a  $\bar{3}$  and a  $6$ . The states of the  $\bar{3}$  are antisymmetric under the interchange of the two light quarks (the  $u$ ,  $d$ , and  $s$  quarks), whereas the states of the  $6$  are symmetric under this interchange. We use a prime to distinguish the  $\Xi_c$  in the  $6$  from the one in the  $\bar{3}$ .



**Figure 3:** The SU(3) multiplets on the second level of the SU(4) multiplet of Fig. 2(b).

**The observed spectra**—(1) The parity of the lightest  $\Lambda_c$  is defined to be positive (as are the parities of the  $p$ ,  $n$ , and  $\Lambda$ ); the limited evidence about its spin is consistent with  $J = 1/2$ . However, none of the other  $J^P$  quantum numbers given in Fig. 1(a) has been measured. Models using spin-spin and spin-orbit interactions between the quarks, with parameters determined using a few of the masses as input, lead to the  $J^P$  assignments shown.<sup>†</sup> There are no surprises: the  $J^P = 1/2^+$  states come first, then the  $J^P = 3/2^+$  states . . .

(2) There is, however, strong evidence that at least some of the  $J^P$  assignments in Fig. 1(a) are correct. As is well known, the successive mass differences between the  $J^P = 3/2^+$  particles, the  $\Delta(1232)^-$ ,  $\Sigma(1385)^-$ ,  $\Xi(1535)^-$ , and  $\Omega^-$ , which lie along the lower left edge of the 20-plet in Fig. 2(a), should be equal according to SU(3); and indeed experimentally they nearly are. Similarly, the successive mass differences between the  $J^P = 1/2^+$   $\Sigma_c(2455)^0$ ,  $\Xi_c^0$ , and  $\Omega_c^0$ ,<sup>‡</sup> the particles along the left edge of Fig. 3(b), should be equal—assuming, of course, that they *do* all have the same  $J^P$ . And the observed differences are  $124.2 \pm 2.9$  MeV and  $119.5 \pm 3.9$  MeV—not perfect, but close. By the same reasoning, since the mass difference between the presumed  $J^P = 3/2^+$   $\Sigma_c(2520)^0$  and  $\Xi_c(2645)^0$  is  $128.1 \pm 1.3$  MeV, the  $3/2^+$   $\Omega_c^0$  should be at about 2774 MeV.

(3) Other evidence comes from the decay of the  $\Lambda_c(2593)$ . The only allowed strong decay is  $\Lambda_c(2593)^+ \rightarrow \Lambda_c^+ \pi \pi$ , and this appears to be dominated by the submode  $\Sigma_c(2455)\pi$ , despite

little available phase space for the latter (the ‘ $Q$ ’ is about 2 MeV, the c.m. decay momentum about 20 MeV/ $c$ ). Thus the decay is almost certainly  $s$ -wave, which, assuming that the  $\Sigma_c(2455)$  does indeed have  $J^P = 1/2^+$ , makes  $J^P = 1/2^-$  for the  $\Lambda_c(2593)$ .

(4) The heavier charmed baryons, such as the  $J^P = 1/2^-$  and  $3/2^-$   $\Lambda_c$ ’s, have much narrower widths than do their strange counterparts, such as the  $\Lambda(1405)$  and  $\Lambda(1520)$ . The clean  $\Lambda_c$  spectrum has in fact been taken to settle the decades-long discussion about the nature of the  $\Lambda(1405)$ —true 3-quark state or mere  $\overline{K}N$  threshold effect?—unambiguously in favor of the first interpretation (which is not to say that the proximity of the  $\overline{K}N$  threshold has no effect on the  $\Lambda(1405)$ ). In fact, models of baryon-resonance spectroscopy should now *start* with the narrow charmed baryons, and work back to those broad old resonances.

**Footnotes:**

\* There is evidence for two more baryons with one  $c$  quark—a  $\Lambda_c(2765)^+$  and a  $\Lambda_c(2880)^+$ —and for a baryon with *two*  $c$  quarks—a  $\Xi_{cc}^+$  at 3519 MeV. However, they have not yet been promoted to the Summary Table. See the Particle Listings.

\*\* For example, there are three  $\Omega_c^0$  states (properly symmetrized states of  $ssc$ ,  $scs$ , and  $css$ ) corresponding to each  $\Omega^-$  ( $sss$ ) state.

† This is not the place to discuss the details of the models, nor to attempt a guide to the literature. See the discovery papers of the various charmed baryons for references to the models that lead to the quantum-number assignments.

‡ A reminder about the Particle Data Group naming scheme: A particle that decays strongly has its mass as part of its name; otherwise it doesn’t. Thus  $\Sigma(1385)$  and  $\Sigma_c(2455)$  but  $\Omega^-$  and  $\Xi_c'$ .