

## CHARMED BARYONS

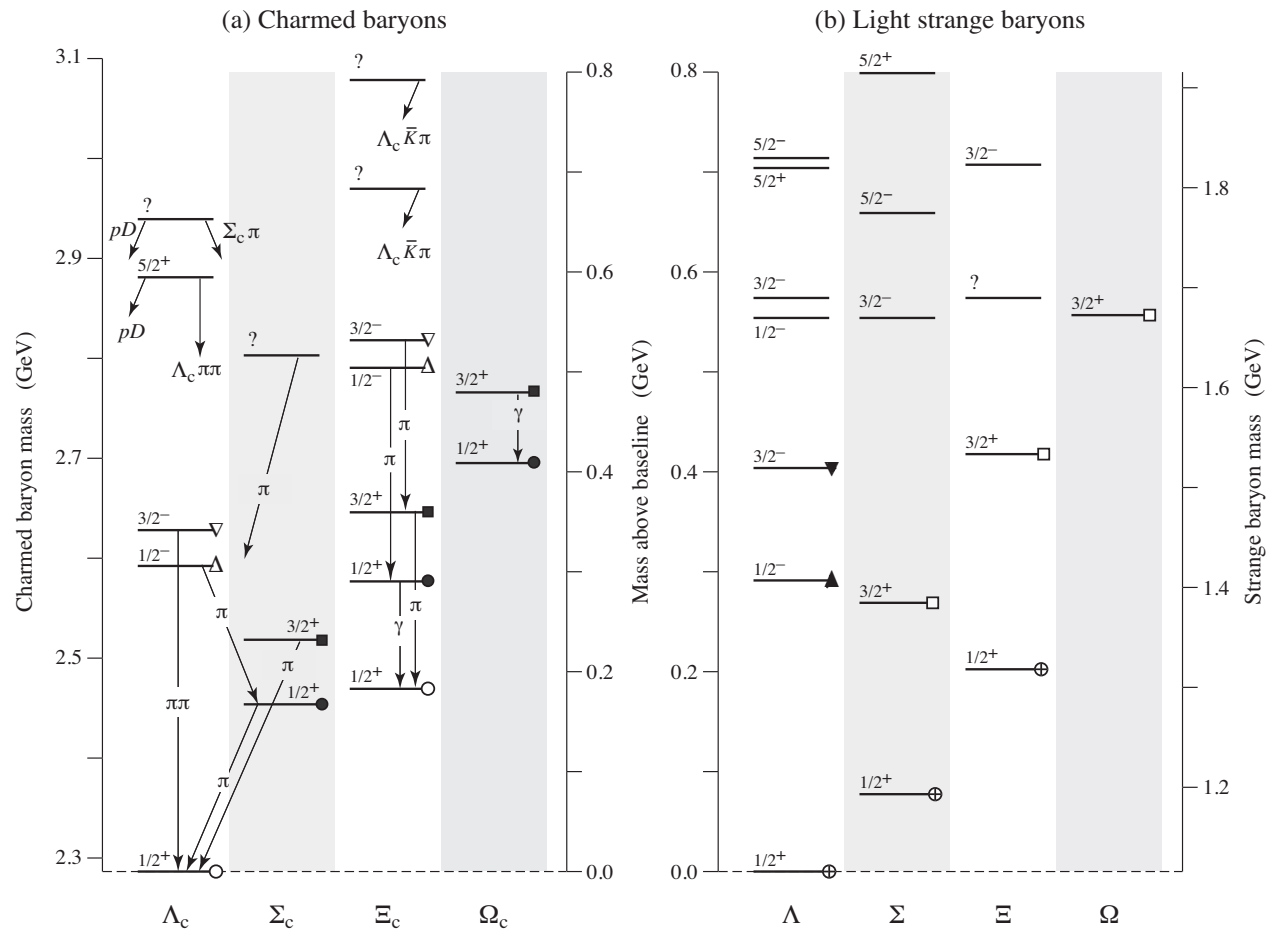
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There are 17 known charmed baryons, and four other candidates not well enough established to be promoted to the Summary Tables.\* Fig. 1(a) shows the mass spectrum, and for comparison Fig. 1(b) shows the spectrum of the lightest strange baryons. The  $\Lambda_c$  and  $\Sigma_c$  spectra ought to look much like the  $\Lambda$  and  $\Sigma$  spectra, since a  $\Lambda_c$  or a  $\Sigma_c$  differs from a  $\Lambda$  or a  $\Sigma$  only by the replacement of the  $s$  quark with 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  $\Xi$  and  $\Omega$  spectra.\*\*

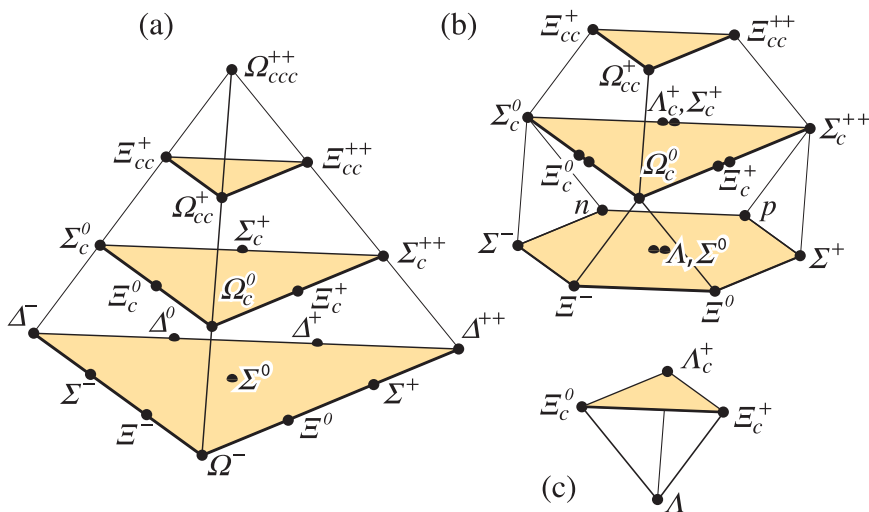
Before discussing the observed spectra, we review the theory of SU(4) multiplets, which tells what charmed baryons to expect; this is essential, because few of the spin-parity values given in Fig. 1(a) have been measured. Rather, they have been assigned in accord with expectations of the theory. However, they are all very likely as shown (see below).

**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 from the bottom level of 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.



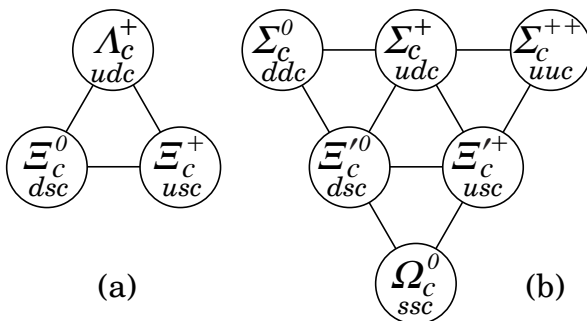
**Fig. 1.** (a) The known charmed baryons, and (b) the lightest “4-star” strange baryons. Note that there are two  $J^P = 1/2^+$   $\Xi_c$  states, and that the lightest  $\Omega_c$  does not have  $J = 3/2$ . The  $J^P = 1/2^+$  states, all tabbed with a circle, belong to the SU(4) multiplet that includes the nucleon; states with a circle with the same *fill* belong to the same SU(3) multiplet within that SU(4) multiplet. Similar remarks apply to the other states: same shape of tab, same SU(4) multiplet; same fill of that shape, same SU(3) multiplet. The  $J^P = 1/2^-$  and  $3/2^-$  states tabbed with triangles complete two SU(4)  $\bar{4}$  multiplets.

The flavor symmetries shown in Fig. 2 are of course 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  $\Omega_c$  has  $J^P = 1/2^+$  and 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. Note that here and in Fig. 3, but not in Fig. 1, each charge state is shown separately.

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  $\Lambda_c$  and  $\Xi_c$  tabbed with open circles in Fig. 1(a) complete a  $J^P = 1/2^+$  SU(3)  $\bar{3}$ -plet, as in (a) here. The  $\Sigma_c$ ,  $\Xi_c$ , and  $\Omega_c$  tabbed with closed circles in Fig. 1(a) complete a  $J^P = 1/2^+$  SU(3) 6-plet, as in (b) here. Together the nine particles complete the charm = +1 level of a  $J^P = 1/2^+$  SU(4)  $20'$ -plet, as in 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, few of the  $J^P$  quantum numbers given in Fig. 1(a) have 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, evidence that many of the  $J^P$  assignments in Fig. 1(a) must be 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 according to SU(3) be about equal; and indeed experimentally they nearly are. In the same way, the 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 about equal—assuming, of course, that they *do* all have the same  $J^P$ . The measured differences are  $125.0 \pm 2.9$  MeV and  $117.3 \pm 3.4$  MeV—not perfect, but close. Similarly, the mass differences between the presumed

$J^P = 3/2^+$   $\Sigma_c(2520)^0$ ,  $\Xi_c(2645)^0$ , and  $\Omega_c(2770)^0$  are  $127.1 \pm 0.8$  MeV and  $120.0 \pm 2.1$  MeV. In Fig. 1(a), these two sets of charm particles are tabbed with solid circles and solid squares.

(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  $\Lambda_c(2593)$ .

### Footnotes:

\* The unpromoted states are a  $\Lambda_c(2765)^+$ , a  $\Xi_c(2930)$ , a  $\Xi_c(3055)$ , and a  $\Xi_c(3123)$ . There is also very weak evidence for a baryon with *two*  $c$  quarks, a  $\Xi_{cc}^+$  at 3519 MeV. 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 has its mass as part of its name if and only if it decays strongly. Thus  $\Sigma(1385)$  and  $\Sigma_c(2455)$  but  $\Omega^-$  and  $\Xi'_c$ .