Where are the missing members of the baryon antidecuplet?

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We analyze what consequences has the observation of exotic pentaquark baryons on the location of the non-exotic baryons belonging to the antidecuplet. We suggest that there must be a new nucleon state at 1650-1690 MeV and a new Σ baryon at 1760-1810 MeV.

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The last 12 months have witnessed a dramatic development in baryon spectroscopy. First, an “exotic” baryon $\Theta^+$ with strangeness $+1$ has been discovered [1] whose mass and narrow width is in agreement with the theoretical prediction [2]. Quite recently, the first observation of a double-strange quadruplet of baryons $\Xi^±_2$ has been reported [3]. Both $\Theta^+$ and $\Xi^±_2$ have quantum numbers such that they can be “made of” minimally four quarks and an antiquark, hence dubbed pentaquarks. Both $\Theta^+$ and $\Xi^±_2$ are expected in the flavor $SU(3)$ antidecuplet of baryons with spin and parity $\frac{1}{2}^+$, forming the upper vertex and the lower edge of the big triangle in the isospin-strangeness diagram, see Fig. 1.

The antidecuplet implies that there are also non-exotic baryons in the middle of the triangle, with quantum numbers of a nucleon and a $\Sigma$ hyperon. These particles have not been identified yet. Finding them is important for understanding the dynamics leading to pentaquarks. In this note, we examine the overall panorama of baryons below 2 GeV with spin and parity $\frac{1}{2}^+$ and suggest where the antidecuplet $N$ and $\Sigma$ can be expected.

To simplify the discussion we put $m_n=m_d=0$ and neglect isotopic splittings throughout the paper. If in addition one takes $m_s=0$ all hadrons appear in exactly degenerate multiplets of the $SU(3)$ flavor group. The splittings inside multiplets and mixings of particles from different multiplets are due to $m_s \neq 0$. In QCD, the only source of $SU(3)$ violation is the mass term of the Lagrangian, $m_s \bar{s}s$, which can be written as $\bar{q} \left( \frac{m_s}{\sqrt{3}} \lambda_3 - \frac{m_s}{\sqrt{3}} \lambda_8 \right) q$. The first (singlet) part leads neither to splitting nor mixing. The second part transforms as the $8^{th}$ component of the octet. To get the splitting/mixing mass matrix, one sandwiches it between the baryon states in question, $m_s < B | \bar{q} \lambda_8 q | B' >$. If $B$, $B'$ belong to octets this matrix element is characterized by two constants, as there are two ways to extract an octet from a direct product of $8 \otimes 8$. If $B$, $B'$ are members of the decuplet or antidecuplet, there is only one constant, as there is a unique way to get the decuplet (antidecuplet) from the product of $10(\bar{10}) \otimes 8$. If the mixing between an octet and an antidecuplet is considered there is also only one constant, as there is only one way to get an antidecuplet from $8 \otimes 8$.

If one temporarily disregards mixings of multiplets, the mass matrices for an octet and a decuplet are:

$$
N_8 = M_8 - \frac{2}{3} x - y, \quad \Delta_{10} = M_{10} - y', \\
\Lambda_8 = M_8 - x, \quad \Sigma_{10} = M_{10}, \\
\Sigma_8 = M_8 + x, \quad \Xi_{10} = M_{10} + y', \\
\Xi_8 = M_8 + \frac{2}{3} x + y, \quad \Omega_{10} = M_{10} + 2y'.
$$

The masses of antidecuplet baryons are also equidistant, as the mass matrices for an octet and a decuplet are:

$$
\Theta^+ = M_{\Xi^+_2} - 2z, \\
N^+_{10} = M_{\Xi^+_2} - z, \\
\Sigma^+_{10} = M_{\Xi^+_2}, \\
\Xi^+_{10} = M_{\Xi^+_2} + z.
$$

The exotic members of the antidecuplet cannot mix up with octet baryons; in principle they can mix up with even higher exotic multiplets but we ignore this possibility. Therefore, the center $M_{\Xi^+_2}$ and the spacing $z$ are found from $\Theta$ and $\Xi^+_2$ masses. We use $\Theta = 1539 \pm 2$ MeV [4] and $\Xi^+_{2} = 1862 \pm 2$ MeV [5] and find $M_{\Xi^+_2} = (\Theta + 2\Xi^+)/3 \approx 1754$ MeV and $z = (\Xi - \Theta)/3 \approx 108$ MeV. Therefore, if $N^+_{10}$ and $\Sigma^+_{10}$ do not mix up with other states their masses are

$$
N^+_{10} \approx 1647 \text{ MeV}, \quad \Sigma^+_{10} \approx 1755 \text{ MeV}.
$$

A consequence of eq. (1) is the Gell-Mann–Okubo relation for octet masses:

$$
\frac{N_8 + \Xi_8}{2} = \frac{3\Lambda_8 + \Sigma_8}{4}.
$$

For the ground-state octet, the least-square fit of the masses averaged over isospin components gives $M_8 = 1151.5$ MeV, $x = 40.2$ MeV, $y = 139.3$ MeV, $\sqrt{\sigma^2} = 3.08$ MeV with GMO relation satisfied within 0.5% accuracy. The equal spacing in the decuplet $(10, \frac{2}{3})$ is also satisfied with high accuracy, with the best fit to the masses $M_{10} = 1382.1$ MeV, $y' = 147.0$ MeV, $\sqrt{\sigma^2} = 3.45$ MeV. The success of this 40-year-old exercise is an unambiguous indication that the mixings of the lowest octet and decuplet with other multiplets are small, as are other possible higher-order $m_s$ corrections to the masses. The GMO relation is valid only in the linear order in $m_s$ and thus it serves as a test for higher-order corrections. Let us apply this test to higher $\frac{1}{2}^+$ multiplets.

The Particle Data Group suggests candidates filling precisely two $\frac{1}{2}^+$ octets in the mass range 1–2 GeV. One
is $N(1710)$, $\Lambda(1810)$, $\Sigma(1880)$ and $\Xi(1950)$. The spin and parity of the last baryon are unknown but we assume that they are $\frac{3}{2}^+$. These masses satisfy the GMO relation \[1\] with an astonishing accuracy of 0.3%. It can be accidental, given that the masses are not known with that precision, however it indicates that it is anyhow a rather “pure” octet with not much room left for its mixing with other multiplets. The situation with the second octet formed by $N(1440)$, $\Lambda(1600)$, $\Sigma(1660)$ and $\Xi(1690)$ is worse: taken at face value these numbers satisfy the GMO relation with an accuracy of 3%. We stress that no other $\frac{3}{2}^+$ particles are mentioned by the PDG, those that appear in the baryon listings fall apparently into these two octets. One octet does not seem to allow considerable mixing; the other can in principle mix with other multiplets, in particular with the antidecuplet.

Before presenting the general scheme of antidecuplet-octet mixing, let us recall the standard theory of the octet-singlet mixing of mesons (see e.g. [5]). Denoting $\theta$ the mixing angle, the GMO relation [4] is modified:

$$m_K^2 = \frac{3(m_1^2 \cos^2 \theta + m_2^2 \sin^2 \theta) + m_{10}^2}{4}, \quad (5)$$

where $m_1(m_2)$ are the masses of the lighter (heavier) iso-singlet mesons, $m_K$ is the mass of the strange and $m_{10}$ is the mass of isotriplet members of the octet. Eq. \[4\] works well for pseudoscalar, vector and tensor mesons, with the mixing angles $\theta = -40.6^\circ, 40^\circ, 30.2^\circ$, respectively.

Let us now derive the general equations for octet-antidecuplet mixing, analogous to eq. \[4\]. There are two particles common to the octet and the antidecuplet: $N$ and $\Sigma$, and only they can mix up. Let us denote by $N_8, N_{10}$ and $\Sigma_8, \Sigma_{10}$ the would-be masses of the appropriate particles before the mixing. These masses include the corrections linear in $m_\Sigma$, as given by eqs. \[12\]. In particular, $N_{10} = 1646$ MeV, $\Sigma_{10} = 1754$ MeV according to eq. \[4\]. $N_8$ and $\Sigma_8$ are a priori unknown. Let the mixing matrix element be $V = <N_{10}|m_\Sigma|N_8> = <\Sigma_{10}|m_\Sigma|\Sigma_8>$. It is important that the two matrix elements are equal since the two corresponding $SU(3)$ Clebsch–Gordan coefficients are equal \[3\]. The physical states are obtained from the diagonalization of the two $2 \times 2$ matrices:

$$\begin{pmatrix} N_8 & V \\ V & N_{10} \end{pmatrix}, \quad \begin{pmatrix} \Sigma_8 & V \\ V & \Sigma_{10} \end{pmatrix}, \quad (6)$$

with the result

$$|N_1| = |N_8| \cos \theta_N + |N_{10}| \sin \theta_N, \quad |N_2| = -|N_8| \sin \theta_N + |N_{10}| \cos \theta_N, \quad \tan 2\theta_N = \frac{2V}{N_8 - N_{10}}, \quad (7)$$

$$|\Sigma_1| = |\Sigma_8| \cos \theta_\Sigma + |\Sigma_{10}| \sin \theta_\Sigma, \quad |\Sigma_2| = -|\Sigma_8| \sin \theta_\Sigma + |\Sigma_{10}| \cos \theta_\Sigma, \quad \tan 2\theta_\Sigma = \frac{2V}{\Sigma_8 - \Sigma_{10}}. \quad (8)$$

and physical masses

$$N_{1,2} = \frac{1}{2} \left( N_{10} + N_8 \pm \sqrt{(N_{10} - N_8)^2 + 4V^2} \right), \quad (9)$$

$$\Sigma_{1,2} = \frac{1}{2} \left( \Sigma_{10} + \Sigma_8 \mp \sqrt{(\Sigma_{10} - \Sigma_8)^2 + 4V^2} \right). \quad (10)$$

The “bare” octet and antidecuplet masses can be expressed through the physical ones and the mixing angles:

$$N_8 = N_1 \cos^2 \theta_N + N_2 \sin^2 \theta_N, \quad N_{10} = N_1 \sin^2 \theta_N + N_2 \cos^2 \theta_N,$$

$$\Sigma_8 = \Sigma_1 \cos^2 \theta_\Sigma + \Sigma_2 \sin^2 \theta_\Sigma, \quad \Sigma_{10} = \Sigma_1 \sin^2 \theta_\Sigma + \Sigma_2 \cos^2 \theta_\Sigma. \quad (11)$$

These masses must be substituted into eq. \[4\] in order to obtain the GMO relation for physical (mixed) members of the octet and the antidecuplet:

$$N_1 \cos^2 \theta_N + N_2 \sin^2 \theta_N) + \Xi_8$$

$$= \frac{3\Lambda + (\Sigma_1 \cos^2 \theta_\Sigma + \Sigma_2 \sin^2 \theta_\Sigma)}{4}. \quad (12)$$

In addition one has relations for physical masses, following from the originally equidistant spectrum of the antidecuplet,

$$z = N_1 \sin^2 \theta_N + N_2 \cos^2 \theta_N - \Theta$$

$$= (\Sigma_1 \sin^2 \theta_\Sigma + \Sigma_2 \cos^2 \theta_\Sigma) - (N_1 \sin^2 \theta_N + N_2 \cos^2 \theta_N)$$

$$= \Xi_8 - (\Sigma_1 \sin^2 \theta_\Sigma + \Sigma_2 \cos^2 \theta_\Sigma), \quad (13)$$

and a relation between $N, \Sigma$ mixing angles

$$(N_2 - N_1) \sin 2\theta_N = (\Sigma_2 - \Sigma_1) \sin 2\theta_\Sigma = -2V. \quad (14)$$

[In the last equation one has to change the sign of the r.h.s. if $(N_{10} - N_8)(\Sigma_{10} - \Sigma_8) < 0$.] A consequence of eqs. \[12\ 13\] is a relation between physical masses, independent of the mixing angles:

$$2(N_1 + N_2 + \Xi_8) = \Sigma_1 + \Sigma_2 + 3\Lambda + \Theta. \quad (15)$$

Eqs. \[12\ 15\] generalize GMO relations for the octet and the antidecuplet in case there is an arbitrary mixing.
between them; these equations are analogous to eq. 5 for strongly mixed mesons.

Recently Jaffe and Wilczek 10 suggested a particular model of a strong antidecuplet-octet mixing with the following mass formula: 
\[ N_1 = M_{20}, \quad \theta = M_0 + m_s, \quad \Lambda = M_0 + m_s + \alpha, \quad N_2 = M_0 + 2m_s + \alpha, \quad \Xi_8 = \Xi_{\Sigma} = M_0 + 2m_s + 2\alpha, \quad \Sigma_2 = M_0 + 3m_s + 2\alpha. \]
This model corresponds to a particular choice of parameters in our general scheme: 
\[ M_0 = \frac{1}{12}(-2m_s + 5\alpha), \quad y = \frac{1}{12}(m_s + 2\alpha), \quad V = \frac{\sqrt{2}}{2}(m_s + \alpha). \]

The ideal mixing model, motivated by the hypothesis of strong diquark correlations in the pentaquark baryons, is however not too realistic. First, it sets \( \Lambda = \Sigma_1 \), whereas the values preferred by the PDG are \( \Lambda = 1600 \text{ MeV} \) and \( \Sigma_1 = 1660 \text{ MeV} \), although with significant error bars. Second, it leads to \( \Xi_8 = 1760 \text{ MeV} \), whereas the only candidate for the octet \( \Xi \) known today is \( \Xi_8 = 1690 \text{ MeV} \). Third, if the NA49 value of \( \Xi_{\Sigma} = 1862 \text{ MeV} \) is confirmed, it is very far from \( \Xi_8 \); Jaffe and Wilczek have them degenerate.

Since the Jaffe–Wilczek model is a particular case of our general formulae for mixing, we can try to get more realistic masses. Assuming that \( \Xi_8(1862) \) is the member of the same antidecuplet as \( \Theta \), we can use the additional information, namely the position of \( \Lambda(1600) \) and \( \Sigma(1880) \) before the mixing is taken into account. It means that actually the number of unknown variables (i.e. the mixing angles \( \theta_{N_{\Sigma}} \) and the masses of the mainly-antidecuplet baryons \( N_2 \) and \( \Sigma_2 \)) is the same as the number of equations, so that they can be determined from the masses of the main-octet baryons \( N_1 = N(1440), \Lambda(1600), \Sigma_1 = \Sigma(1660) \) and \( \Xi(1690) \). Taken literally, however, these numbers do not lead to any reasonable solution of eqs. 12, 14. Solutions appear if one shifts somewhat the above PDG-preferred values inside the error bars. For example, taking \( N_1 = 1470, \Lambda = 1570, \Sigma_1 = 1635, \Xi = 1700 \) and solving eqs. 12, 14 we obtain the following mixing angles and the masses of mainly-antidecuplet baryons:

\[ \theta_N = 13.1^\circ, \quad \theta_\Sigma = 19.1^\circ, \quad N_2 = 1656 \text{ MeV}, \quad \Sigma_2 = 1768 \text{ MeV}. \] (16)

Another choice, \( N_1 = 1460, \Lambda = 1575, \Sigma_1 = 1630, \Xi = 1710 \), gives

\[ \theta_N = 21.9^\circ, \quad \theta_\Sigma = 31.1^\circ, \quad N_2 = 1676 \text{ MeV}, \quad \Sigma_2 = 1799 \text{ MeV}. \] (17)

We see thus that there is an uncertainty in predicting the \( N_2, \Sigma_2 \) masses, which is due to the experimental uncertainty in the mainly-octet masses. A general feature is that mixing pushes both \( N_2 \) and \( \Sigma_2 \) masses to somewhat higher values than those following from the antidecuplet equidistant splitting, eq. 8. It is interesting to note that the recent search for narrow resonances in the partial-wave analysis of the elastic \( \pi N \) scattering 12 points out a candidate with the mass 1680 MeV.

We remind that we have “pulled out” the \( N(1710) \) and \( \Xi(1880) \) resonances as presumably belonging to another octet, therefore we are now discussing new unobserved resonances. The larger the mixing angle, more strangeness is “washed out” from the Roper resonance \( N(1440) \) and brought into the second nucleon \( N_2 \) which will then have a larger branching into \( N\eta \) decay. As the mixing angle rises, the mass of \( N_2 \) rises too, and the resonance becomes broader as it mixes up with an extremely broad resonance \( N(1440) \). Since no broad \( \frac{1}{2}^+ \) nucleon resonance is known in this mass range, it means that mixing cannot be large and hence \( N_2 \) cannot be considerably heavier than the ‘equidistant’ value 8. Our “educated guess” is that the new \( N \) resonance must be in the 1650-1690 MeV range and the new \( \Sigma \) resonance must be in the 1760-1810 MeV range.

We note on this occasion that there is a weak (one-star) evidence for a \( \frac{1}{2}^+ \) \( \Sigma \) resonance at 1770 MeV with a width of 70 MeV in the PDG baryon listings: it might be a “crypto-exotic” partner of the more pronounced exotic \( \Theta \) and \( \Xi_{\Sigma} \). Just because it is not exotic the \( \Sigma \) resonance from the antidecuplet cannot and probably does mix with \( \Sigma \) from a nearby octet and hence must be more broad than the narrow \( \Theta \) and \( \Xi_{\Sigma} \). The same is true for the last nucleon member of the antidecuplet.

Is the value of the spacing in the antidecuplet \( z = 108 \text{ MeV} \) reasonable? In ref. 8 the spacing has been estimated as 180 MeV using the evaluation 11 of \( \Sigma = 45 \text{ MeV} \) for the nucleon sigma term. Since then \( \Sigma \) has been re-evaluated with a significantly larger result \( \Sigma = 67 \pm 6 \text{ MeV} \). If one uses this value the antidecuplet splitting reduces considerably. Let us remind a few simple equations from ref. 8. The splittings in the ground-state octet, decuplet and antidecuplet have been determined there by three constants \( \alpha, \beta, \gamma \) such that

\[ x = \frac{1}{10} \alpha + \frac{3}{20} \gamma, \quad y = \frac{1}{8} \alpha + \beta - \frac{5}{16} \gamma, \] (18)
\[ z = \frac{1}{8} \alpha + \beta + \frac{1}{16} \gamma, \quad \alpha + \beta = \frac{2 m_s}{3 m_u + m_d} \Sigma, \]

where \( x, y \) characterize the splitting in the octet and the decuplet (see eqs. 13, 14). Eq. 18 has been derived in the leading and subleading orders in the number of colors \( N_c \), implying \( y = y' \) which is well satisfied. The combined least-square fit to the masses of the octet and the decuplet gives \( x = 37.13, y = 145.9, \sqrt{\sigma^2} = 4 \text{ MeV} \). We take the quark mass ratio from the Gell-Mann–Oakes–Renner formulae \( m_s/(m_u + m_d) = 12.9 \) and the nucleon sigma term \( \Sigma = 72 \text{ MeV} \). We get then from eq. 18 \( z = 108.8 \text{ MeV} \) which, being tripled, is compatible with the mass difference \( \Xi_{\Sigma}(1862) - \Theta(1539) \). It should be noted that there can be certain \( 1/N_2^2 \) corrections to eq. 18. In short, one can explain the \( \Xi_{\Sigma} - \Theta \) splitting.

Assuming \( \Xi_{\Sigma} \) and \( \Theta \) are members of the same \( \frac{1}{2}^+ \) antidecuplet, their widths are related by \( SU(3) \) Clebsch–Gordan coefficients (up to \( O(m_s) \) corrections), and proportional to the cube of meson momenta. Adjusting the
Many-body decays of $\Xi^+$ and $\Xi^-$ into an octet baryon and a pseudoscalar meson. Owing to

$$\Gamma(\Xi^+ \to \Sigma^- K^-) \approx 0.87 \Gamma_{\Theta},$$
$$\Gamma(\Xi^- \to \Sigma^- K^+) \approx 1.68 \Gamma_{\Theta}. \quad (19)$$

Many-body decays of $\Xi$, add potentially at least as much to the total width which we thus estimate as $\Gamma_{\Xi_{3/2}} = 5 \Gamma_{\Theta}$. The restriction $\Gamma_{\Xi_{3/2}} < 18$ MeV is consistent with the most stringent experimental limit on the $\Theta^+$'s width $\Gamma_{\Theta} < 9$ MeV and with even more restrictive indirect estimates of a few MeV or less.

Why are $\Theta^+$ and $\Xi^+$ so narrow? The small width prediction of ref. $|$ is rather technical and calls for a “physical” explanation. To answer the question one has first to explain why pentaquark baryons are unexpected. Indeed, a naive constituent quark model with quark mass $M \approx 350$ MeV (such that vector mesons are approximately twice and nucleons thrice this mass) predicts $\Theta^+$ at about $350 \times 5 = 1750$ MeV, plus 100–150 MeV for strangeness.

The crucial physics ignored in this naive estimate is the spontaneous breaking of chiral symmetry in QCD. It is due to the SBCS that the nearly massless quarks of the QCD Lagrangian obtain a large mass of about 350 MeV. Simultaneously, the massive (“constituent”) quarks must interact with light pions and kaons, and very strongly. Chiral forces are probably more important for binding constituent quarks in baryons, than any other force.

In this picture, pentaquarks are baryons in which the additional quark-antiquark pair appears in the form of an excitation of the chiral field inside baryons. (It is not a pseudoscalar meson - baryon molecule though.) The energy penalty for an additional pair is not twice the constituent quark mass but something much less: it is the energy of the chiral excitation, which is proportional to the inverse size of the baryon. It tends to zero in the imaginary limit of large-size baryons. This is a qualitative explanation why exotic baryons are anomalously light.

Even if the three ‘valence’ quarks are not too relativistic, the quark-antiquark pair inside the pion or kaon field is always relativistic. The non-relativistic wave-function description of pentaquarks makes no sense. “Measuring” the quark position with an accuracy higher than the pion Compton wave length of 1 fm produces a new pion, i.e. a new quark-antiquark pair. What makes sense in this situation is describing baryons in the infinite momentum frame. In that frame there can be no production and annihilation of quarks, and the baryon wave function falls into separate sectors of the Fock space: three quarks, five quarks, etc. The difference between the ordinary nucleon and $\Theta^+$ is that the nucleon has a three-quark component (but necessarily also has a five-quark component) while $\Theta^+$'s Fock space starts from the five-quark component.

One can now consider the decay amplitude of $\Theta^+$ or $\Xi$ into an octet baryon and a pseudoscalar meson. Owing to
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