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Systematics of exotic cascade decays

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Theoretical considerations prompted by the discovery of the exotic $\Theta^+(uudd\overline{s})$ led us to propose a dynamical picture emphasizing the role of diquark correlations, which are also useful in elucidating other aspects of low-energy QCD. A notable prediction of this picture is the existence of new exotic and nonexotic $S=-2$ "cascade" baryons with specific, characteristic properties. We argue here that recent observations by the NA49 Collaboration are broadly consistent with our predictions, and propose further tests.

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I. INTRODUCTION

Recently we proposed that the systematics of exotic baryons in QCD can be explained by diquark correlations [1]. If this picture is correct, the lightest and only prominent $qqqq\overline{q}$ baryons made of light (u, d, s) quarks will form an antidecuplet of $SU(3)_f$ with positive parity, accompanied by a nearly degenerate octet also containing large $qqqq\overline{q}$ components. The most unusual states in this multiplet, aside from the original $\Theta^+(uudd\overline{s})$ [2] which motivated the study, are the quartet of $I(\text{isospin})=3/2$, $S(\text{strangeness})=-2$, "cascades," which we predicted to be quite light and quite narrow [1]. The diquark picture is not the only proposed explanation for the observed exotic baryons. The existence of a prominent exotic baryon antidecuplet is a long-standing prediction of the chiral soliton model [3]. Indeed, the experiment in which the Θ^+ was first reported was motivated by the work of Diakonov, Petrov, and Polyakov [3]. Since that discovery, many different models have been proposed for the Θ^+ and related states [4].

More experimental input and theoretical analysis will be needed to distinguish among different dynamical pictures of exotic baryons. Definitive statements about the internal structure of these new baryons likely will not be possible until realistic (i.e., unquenched, light-quark), high-statistics lattice studies are carried out. The first lattice studies employed sources which seem to be poorly matched to the diquark picture [5], but more appropriate sources have been proposed [6] and new studies are underway. Below we review the foundations of the diquark picture and provide a guide to its implications for exotic cascades and their nonexotic partners.

We also explore, specifically, what can be learned from the decays of the exotic and nonexotic $qqqq\overline{q}$ cascade states [7]. Our work is motivated in part by the recent report of a $\Xi^{--}(ddss\overline{u})$ near 1860 MeV [8]. The report needs confirmation. On the other hand, the Θ^+ now seems rather well founded, and given its existence very general arguments, of which diquark dyanmics are a special case, require light exotic cascades to till out the antidecuplet. The phenomenological implications discussed here follow from the diquark picture of exotic dynamics and are largely independent of whether or not Ref. [8] is confirmed. For purposes of concreteness, we henceforth assume that the observations reported in Refs. [8] and [9] reflect reality.

Quite a bit can already be inferred from the observation (and nonobservation) of various decay modes reported by the NA49 Collaboration. First, of course, the $\Xi^{--}(1860)$ provides further evidence of the antidecuplet begun with the $\Theta^+(1540)$. Second, the report of a nearly degenerate $\Xi^-(1855)$ decaying into the well-known $\Xi^*(1530)$ *and* the apparent absence of a signal for a nearby Ξ^+ decaying into the $\Xi^*(1530)$ [9] together suggest that there is a nonexotic, $I=1/2$, multiplet of cascades at the nearly the same mass as the $\Xi^{--}(1860)$. NA49 also reports evidence for a $\Xi^0(1860)$ decaying into $\Xi(1320)\pi$. While this reenforces the evidence for narrow cascades in this mass range, it does not distinguish between $I=1/2$ and $I=3/2$. The possible existence of an $I=1/2$ multiplet among this complex of cascades around 1860 MeV could be confirmed by looking for the decays $\Xi^-(1855)\to\Lambda K^-$ and $\Xi^0(1860)\to\Lambda\overline{K}^0$, which should be visible in the NA49 apparatus. When an experiment sensitive to neutral particles (π^0's and/or neutrons) becomes available, several further checks will be possible. Should the existence of both $I=1/2$ and $I=3/2$ cascade multiplets be confirmed, it would be strong evidence for the appropriateness of the quark picture of the exotic spectrum, which requires a roughly degenerate octet and antidecuplet. By way of contrast chiral soliton models, while they do, generically, predict the existence of excited octets, together with many other $SU(3)_f$ representations, provide no natural reason for the octet to be nearly degenerate with the antidecuplet [3,10]. Finally, the observed decay of the $\Xi^-(1855)$ provides some indication concerning its spin and parity. The spin and parity of the Θ^+ and Ξ^{--} are unknown, although there is some indication, from the absence of structure in the production angular distribution [11], that the Θ^+ has $J=1/2$. A measurement of the spin and parity would discriminate between uncorrelated quark models, which predict negative parity, and both correlated quark models and chiral soliton models, which predict positive parity. Specifically, the observation of $\Xi^-(1855)\to\Xi^{*0}(1530)\pi^-$ disfavors $J^{\Pi}=1/2^-$.

II. CONSEQUENCES OF DIQUARK DYNAMICS

Here we summarize the diquark picture of exotic dynamics and its most striking predictions. We assume that quarks, when possible, correlate strongly in the channel which is antisymmetric in color, spin, and flavor. This channel is favored both by gluon exchange [12] and by instanton interactions [13]. For light quarks (u, d, and s) the resulting diquark $\mathbb{Q}$ is a color and flavor-$SU(3)$ antitriplet with $J^{\Pi}=0^{+}$. The correlation is strongest for massless (u and d) quarks and decreases as the mass of one quark or the other increases. It is diminished for *ds* and *su* pairs. In the heavy-quark limit it scales like $1/m_1m_2$ and is probably negligible, except perhaps for charm-light combinations [14]. Diquarks with other color and spin quantum numbers are assumed to be less favored energetically. Of course the disfavored diquark (flavor symmetric, color antisymmetric, $J=1$) also appears in the hadron spectrum—most notably in the $3/2^{+}$ baryon decuplet. A simple analysis of the masses of strange (Λ, Σ, Σ^{*}) or charm (Λ_c, Σ_c, Σ_c^{*}) baryons indicates an approximately 210 MeV energy difference between the disfavored and favored (*ud*) diquarks. This is a significant difference, enough to make exotic mesons and baryons composed of disfavored diquarks heavy, broad, and prone to be indistinguishable from the continuum of ordinary meson and baryon states, into which they can fall apart without suppression [15]. Dominance of the favored diquark leads to the many predictions for exotic spectroscopy.

(i) No light exotic $qq\bar{q}\bar{q}$ mesons will ever be seen, because the flavor content of $\mathbb{Q}\otimes\bar{\mathbb{Q}}$ is $3_f\otimes\bar{3}_f=1_f\oplus 8_f$ [15,16], which are the same representations as ordinary $q\bar{q}$ mesons. (This does not preclude the possibility of manifestly exotic meson resonances involving favored diquarks with heavy flavors, such as $cs\bar{u}\bar{d}$ [14].)

(ii) Instead, the only prominent light $qq\bar{q}\bar{q}$ mesons will be a nearly ideally mixed octet and singlet of $J^{\Pi}=0^{+}$ mesons. These can perhaps be identified with the $f_0(600)$, $\kappa(800)$, $f_0(980)$, and $a_0(980)$ [16]. These light scalar mesons have always posed classification problems for quark models, and there is an entire additional nonet of scalar mesons in the 1300–1500 MeV range, where $q\bar{q}$ mesons would be expected to lie. Because they are not manifestly exotic, however, the classification of the light scalars as $qq\bar{q}\bar{q}$ remains controversial [17].

(iii) The only light-quark exotic baryons made of four quarks and an antiquark will lie in an antidecuplet of $SU(3)_f$, which will be nearly ideally mixed with an octet. The nonexotic states in these multiplets will further mix with ordinary qqq baryons. Since diquarks are $SU(3)_f$ antitriplets, the only way to make an exotic out of two diquarks and an antiquark is to combine the diquarks symmetrically in flavor, $[\bar{3}_f\otimes\bar{3}_f]_{\mathcal{S}}=\bar{6}_f$, and then couple the antiquark. The flavor content of the resulting $qqqq\bar{q}$ states is then $\bar{6}_f\otimes\bar{3}_f=8_f\oplus\overline{10}_f$ [1]. Other approaches to exotic spectroscopy predict a much richer spectrum of exotics including 27_f and 35_f multiplets [4]. A particularly notable difference is the absence in the diquark picture of an isovector analogue of the $\Theta^{+}(1540)$, with $S=+1$ and charges $Q=0$, 1, and 2 (a state which occurs in the 27_f and other exotic multiplets, but not in the $\overline{10}_f$), at low mass, which seems to be a robust prediction of chiral soliton models [18] and which has been sought without success in analyses of $K^{+}p$ data [19].

(iv) The mass splittings of the $[\mathbb{Q}\otimes\mathbb{Q}]_{\mathcal{S}}\otimes\bar{q}$ octet and antidecuplet baryons, computed to first order in m_s, yield a spectrum (as discussed in Ref. [1]) which includes the $\Theta^{+}(1540)$, two nucleons, N and N', two Σ's, Σ and Σ', a Λ, and *two multiplets of cascades*: one in the antidecuplet with $I=3/2$, which includes the exotic $\Xi^{+}(uuss\bar{d})$ and $\Xi^{--}(ddss\bar{u})$, and the other in the octet with $I=1/2$. The mass spectrum proposed in Ref. [1] follows from the assumption that the fundamental forces between quarks and antiquarks are flavor independent. Then $SU(3)_f$ violation introduces one parameter $\langle\bar{6}_f||\mathcal{H}_8||\bar{6}_f\rangle$ for the $\{qqqq\}_{\bar{6}_f}$ and another parameter $\langle\bar{3}_f||\mathcal{H}_8||\bar{3}_f\rangle$ for the $\bar{q}$. The exotic baryon mass does not depend on how the $\bar{6}_f$ and $\bar{3}_f$ are finally coupled. This model gives ideal mixing: the number of $s+\bar{s}$ quarks in a hadron is a good quantum number, so the light nucleon N^{+} is $uudd\bar{d}$, while the heavy nucleon N'^{+} is $uuds\bar{s}$. Likewise the light Σ^{+} is $uuds\bar{d}$ and the heavy Σ'^{+} is $uuss\bar{s}$. The masses of the 8_f and $\overline{10}_f$ baryons are then given by $M(N)=M_0$, $M(\Theta)=M_0+\mu$, $M(\Lambda)=M(\Sigma)=M_0+\mu+\alpha$, $M(N')=M_0+2\mu+\alpha$, $M(\Xi_{\overline{10}})=M(\Xi_8)=M_0+2\mu+2\alpha$, and $M(\Sigma')=M_0+3\mu+2\alpha$, where M_0 is the common mass in the $SU(3)_f$ symmetry limit, and μ and α are linear combinations of the $\bar{3}_f$ and $\bar{6}_f$ symmetry breaking invariant matrix elements. Ideal mixing is only an approximate symmetry for well-known mesons (e.g., ρ, ω, ϕ), so one should not expect high accuracy here. To emphasize this we round all masses to the nearest 50 MeV.[1] An analysis of the complete baryon resonance spectrum [20] suggests that the $N(1440)^{1/2^{+}}$ and $\Sigma(1660)^{1/2^{+}}$ should be identified with the N and Σ $qqqq\bar{q}$ states. This allows a determination of α and μ entirely within the $qqqq\bar{q}$ sector, with the result $\alpha\approx 100$ MeV and $\mu\approx 100$ MeV. The resulting mass predictions are $M(N)\approx 1450$, $M(\Theta)\approx 1550$, $M(\Lambda)\approx M(\Sigma)\approx 1650$, $M(N')\approx 1750$, $M(\Xi_{\overline{10}})\approx M(\Xi_8)\approx 1850$, and $M(\Sigma')\approx 1950$. The Ξ mass is closer to the mass reported by NA49 than our original estimate. The N' is predicted at 1750 MeV, close to the $N(1710)^{1/2^{+}}$. Our model is obviously crude. However, we know of no framework for multiquark dynamics—other than lattice QCD—which offers a more accurate analysis.

(v) The exotic antidecuplet baryons should have spin-parity $1/2^{+}$ and be accompanied by nearby states with $J^{\Pi}=3/2^{+}$ [1,21]: $[\mathbb{Q}\otimes\mathbb{Q}]_{\mathcal{S}}$ must be in the P wave to satisfy

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[1] In Ref. [1] we took $\alpha=60$ MeV from an analysis of octet baryon masses and thereby estimated $M(\Xi)=1750$ MeV.

Bose statistics. This $\ell = 1$ system can couple to the antiquark to give either $J^{\Pi} = 3/2^{+}$ or $1/2^{+}$.

(vi) Charm and bottom analogues of the $\Theta^{+}(uudd\overline{s})$ with quark content $uudd\overline{c}$ and $uudd\overline{b}$ may be stable against strong decay: The strong decay thresholds for these states depend on the pseudoscalar meson masses, which grow like the square root of the quark masses. Thus, for example, the threshold for $\Theta^{0}_{c}(uudd\overline{c}) \to pD^{-}$ is relatively higher than the threshold for $\Theta^{+}_{s}(uudd\overline{s}) \to nK^{+}$ [1].

(vii) Configurations in which diquarks are in relative S waves will experience a repulsive interaction due to Pauli blocking [1]. States affected by this include the nonexotic nonet of baryons of the form $[\mathbb{Q}\otimes\mathbb{Q}]_{\mathcal{A}}\otimes\overline{q}$ with negative parity and flavor content $3_f \otimes \overline{3}_f = 1_f \oplus 8_f$, and the H dibaryon, $[\mathbb{Q}\otimes\mathbb{Q}\otimes\mathbb{Q}]_{\mathcal{A}}$, a flavor singlet. These states will be heavier and less prominent as a result.

(viii) Our principal focus here is on the cascade states in the $SU(3)$-flavor antidecuplet and octet. We denote the antidecuplet $I = 3/2$ cascade state with charge Q by $\Xi^{Q}_{3/2}$ and the octet $I = 1/2$ cascade state by $\Xi^{Q}_{1/2}$. The antidecuplet and octet cascade states share common color and spin wave functions and therefore should be close in mass, except for the possibility that the octet states could mix with nearby qqq states. Isospin violating mixing between the $\Xi^{Q}_{3/2}$ and $\Xi^{Q}_{1/2}$ should be small unless they are accidentally highly degenerate. Indeed, the $\{\Xi^{0}_{3/2}, \Xi^{0}_{1/2}\}$ and $\{\Xi^{-}_{3/2}, \Xi^{-}_{1/2}\}$ are the only pairs of octet and antidecuplet states with the same charge and strangeness which *should not* mix significantly. In contrast, for example, the $N_{\overline{10}}$ and N_{8} should mix strongly to diagonalize strange quark number. As a result all the $qqqq\overline{q}$ cascade states should respect selection rules which follow from their isospin and $SU(3)_f$ quantum numbers. The states are expected to have $J^{\Pi} = 1/2^{+}$ or $J^{\Pi} = 3/2^{+}$. If the $\Theta^{+}(1540)$ and the exotic cascades have the same spin-parity, then their widths can be related by assuming $SU(3)_f$ symmetry for the matrix element and correcting for phase space. This should be reliable at the level of typical $SU(3)_f$ symmetry violation—i.e., $\sim 30\%$. This estimate gives widths of the order of 3.5 times the width of the $\Theta^{+}(1540)$ for exotic cascades with masses of 1860 MeV. Although no symmetry applies, we also expect the related $J^{\Pi} = 3/2^{+}$ states to be narrow, since the underlying color dynamics is common to both.

III. INTERPRETATION OF THE NA49 OBSERVATIONS

The cascades observed by NA49 appear to decay into either the $\Xi(1320)$ $(J^{\Pi} = 1/2^{+})$ or the $\Xi^{*}(1530)$ $(J^{\Pi} = 3/2^{+})$. For simplicity we refer to the former as the Ξ and the latter as the Ξ^{*}. To avoid confusion, we will denote the cascade states observed by NA49 by "$\boldsymbol{\Xi}^{Q}$" (where Q is the charge) unprejudiced by theoretical interpretation. In contrast, when we identify and discuss antidecuplet and octet states we denote them $\Xi^{Q}_{3/2}$ and $\Xi^{Q}_{1/2}$, respectively. NA49 can only reconstruct final states without neutral particles. Perusal of the PDG tables suggests the following possible decays of their $\boldsymbol{\Xi}$ states to Ξ or Ξ^{*} can be observed:

$$\boldsymbol{\Xi}^{--} \to \Xi^{-}\pi^{-}, \tag{1}$$

$$\boldsymbol{\Xi}^{-} \to \Xi^{*0}\pi^{-}, \tag{2}$$

$$\boldsymbol{\Xi}^{0} \to \Xi^{-}\pi^{+}, \tag{3}$$

$$\boldsymbol{\Xi}^{+} \to \Xi^{*0}\pi^{+}. \tag{4}$$

As of this writing, NA49 has presented evidence for decays (1), (2), and (3). They have looked for, but have not seen, decay (4) [8,9]. In all cases the masses are approximately 1860 MeV and the widths are below the experimental resolution of 18 MeV. Although some of these results are preliminary and all are unconfirmed, for the purposes of this analysis we accept them and consider their consequences. We discuss the flavor consequences of each decay in turn, and then return to discuss spin and parity.

A. Flavor classification

1. $\boldsymbol{\Xi}^{--} \to \Xi^{-}\pi^{-}$

This decay is allowed by both isospin and $SU(3)_f$ symmetry. It clearly identifies $\boldsymbol{\Xi}^{--}$ to be a member of the antidecuplet with $I_3 = -3/2$, in our notation $\Xi^{--}_{3/2}$, with quark content $ddss\overline{u}$. $SU(3)_f$ symmetry predicts that the amplitude for $\Xi^{--}_{3/2} \to \Sigma^{-}K^{-}$ is the same as $\Xi^{--}_{3/2} \to \Xi^{-}\pi^{-}$. Unfortunately this decay cannot be seen at NA49 because $\Sigma^{-} \to nK^{-}$, and the neutron cannot be seen. The decay $\Xi^{--}_{3/2} \to \Xi^{*-}\pi^{-}$ (which also cannot be seen by NA49) is forbidden by $SU(3)_f$ symmetry because $10_f \otimes 8_f \not\supset \overline{10}_f$, and should be suppressed. Given that, $\Xi^{-}\pi^{-}$ and $\Sigma^{-}K^{-}$ are the only two-body decay modes for the $\Xi^{--}_{3/2}$ and its width can be related to the width of the $\Theta^{+}(1540)$. At a mass of 1860 MeV and assuming P-wave phase space, as suggested by the diquark picture, we estimate

$$\frac{\Gamma[\Xi^{--}_{3/2}(1860)]}{\Gamma[\Theta^{+}(1540)]} \approx 3.4, \quad \frac{\mathrm{BR}[\Xi^{--}_{3/2}(1860) \to \Sigma^{-}K^{-}]}{\mathrm{BR}[\Xi^{--}_{3/2}(1860) \to \Xi^{-}\pi^{-}]} \approx 0.5.$$

2. $\boldsymbol{\Xi}^{-} \to \Xi^{*0}\pi^{-}$

This decay is in many ways the most interesting reported by NA49. It is tempting to identify the $\boldsymbol{\Xi}^{-}$ with the $\Xi^{-}_{3/2}$, the isospin partner of the $\Xi^{--}_{3/2}$. If so, the decay to $\Xi^{*0}\pi^{-}$ is allowed by isospin, but the $\Xi^{-}_{3/2}$ is in the antidecuplet and the decay is forbidden by $SU(3)_f$, since $10_f \otimes 8_f \not\supset \overline{10}_f$. In contrast, the decays $\Xi^{-}_{3/2} \to \Xi^{0}\pi^{-}/\Xi^{-}\pi^{0}$ (which cannot be seen by NA49) are allowed by isospin and $SU(3)_f$ and predicted to go at the same rate as $\Xi^{--}_{3/2} \to \Xi^{-}\pi^{-}$. Furthermore, these decays have more phase space than $\boldsymbol{\Xi}^{-} \to \Xi^{*0}\pi^{-}$ (the ratio of P-wave phase space factors is approximately 4.5). Thus, if $\boldsymbol{\Xi}^{-}$ is in the antidecuplet, both phase space and the $SU(3)_f$

selection rule favor $\Xi^- \to \Xi^0 \pi^-$ over $\Xi^- \to \Xi^{*0} \pi^-$, and NA49 would have to be seeing a strongly suppressed mode.

Provided the Ξ^- is not produced much more copiously than Ξ^{--} and the NA49 sensitivity to the mode $\Xi^- \to \Xi^{0*} \pi^-$ is not much greater than the sensitivity to $\Xi^{--} \to \Xi^- \pi^-$, both of which are reasonable assumptions, then either $SU(3)_f$ is badly violated or Ξ^- is not in an antidecuplet. The first alternative—$SU(3)_f$ violation—predicts a healthy rate for $\Xi^+ \to \Xi^{*0} \pi^+$, which has not been seen (see below). So we propose that the decay $\Xi^- \to \Xi^{*0} \pi^-$ identifies the Ξ^- to be a member of an octet, presumably the octet expected in the diquark picture. If this is correct, then the NA49 data contain evidence for *both* octet and antidecuplet cascades near 1860 MeV.

Since this is an important issue, the classification of the Ξ^- must be confirmed. Note that the negatively charged partner $\Xi^-_{3/2}$ of the $\Xi^{--}_{3/2}$ is also expected to lie in this mass region. Both the $\Xi^-_{3/2}$ and $\Xi^-_{1/2}$ can decay to $\Xi^- \pi^0 / \Xi^0 \pi^-$, so this decay channel may show rich structure. If there were no $I = 1/2$ state, then the Ξ^{--} and Ξ^- are both members of the same $I = 3/2$ multiplet and the rate for $\Xi^{--} \to \Xi^- \pi^-$ and $\Xi^- \to \Xi^0 \pi^- / \Xi^- \pi^0$ should be the same, and the ratio of branching ratios,

$$\frac{\mathrm{BR}[\Xi^-_{3/2}(1855) \to \Xi^- \pi^0]}{\mathrm{BR}[\Xi^-_{3/2}(1855) \to \Xi^0 \pi^-]} = 2,$$

is determined by isospin symmetry alone. In contrast, if only the $I = 1/2$ octet state $\Xi^-_{1/2}$ is present, then the ratio is inverted:

$$\frac{\mathrm{BR}[\Xi^-_{1/2}(1855) \to \Xi^- \pi^0]}{\mathrm{BR}[\Xi^-_{1/2}(1855) \to \Xi^0 \pi^-]} = \frac{1}{2}.$$

Deviation from these simple isospin relations would signal the presence of both $I = 1/2$ and $I = 3/2$. Study of this decay channel must await an experiment sensitive to neutrals. NA49 can look for the decay $\Xi^-_{1/2} \to \Lambda K^-$, which is allowed by $SU(3)_f$ and has phase space comparable to the decay $\Xi^-_{1/2} \to \Xi \pi$. Observation of this decay mode would confirm the existence of an $I = 1/2$ component of the Ξ^-, because ΛK^- cannot have $I = 3/2$. Unfortunately we cannot use symmetry to predict a rate for $\Xi^-_{1/2} \to \Lambda K^-$ on the basis of the observation of $\Xi^-_{1/2} \to \Xi^{*0} \pi^-$ or $\Xi^{--}_{3/2} \to \Xi^- \pi^-$, because the decays involve different $SU(3)_f$ reduced matrix elements.

3. $\Xi^0 \to \Xi^- \pi^+$

Both the $\Xi^0_{3/2}$ partner of the $\Xi^{--}_{3/2}$ and the $\Xi^0_{1/2}$ partner of the $\Xi^-_{1/2}$ are expected to decay into $\Xi^- \pi^+$. Isospin invariance predicts the rate for $\Xi^0_{3/2} \to \Xi^- \pi^+$ to be 1/3 that of $\Xi^{--} \to \Xi^- \pi^-$. On the other hand, the rate for $\Xi^0_{1/2} \to \Xi^- \pi^+$ should be 2/3 of the total rate of $\Xi^-_{1/2} \to \Xi \pi$. The observation of this decay mode by NA49 confirms the general existence of cascades in the 1860 MeV region, but does not discriminate between the $I = 1/2$ octet and $I = 3/2$ antidecuplet. If we have interpreted decays (1) and (2) correctly, *both states are needed here*. Careful measurement and comparisons of the decays $\Xi^- \to \Xi^- \pi^+$ and $\Xi^- \to \Xi^0 \pi^0$ would help sort out the isospin structure. This also awaits an experiment sensitive to neutrals. The existence of an $I = 1/2$ component in the Ξ^0 could be confirmed by searching for the decay $\Xi^0 \to \Lambda \overline{K}^0$, which could be seen at NA49 as ΛK_S. Failure to observe it at a level of sensitivity comparable to decay (3) would suggest $I = 3/2$. Unfortunately we cannot use $SU(3)_f$ symmetry to predict the rate for $\Xi^0_{1/2} \to \Lambda \overline{K}^0$ from the observation of $\Xi^0_{1/2} \to \Xi^- \pi^+$ because there are two $SU(3)_f$ reduced matrix elements in $8_f \otimes 8_f \supset 8_f$.

TABLE I. Orbital angular momentum (in spectroscopic notation) and center-of-mass momentum (in MeV) for the Ξ decay channels reported by NA49, for various spin-parity assignments of the Ξ's.

J^Π	$1/2^+$	$1/2^-$	$3/2^+$	$3/2^-$	$p_{\mathrm{c.m.}}$
$\Xi^{--} \to \Xi^- \pi^-$	P	S	P	D	445 MeV
$\Xi^- \to \Xi^{*0} \pi^-$	P	D	P	S	267 MeV
$\Xi^0 \to \Xi^- \pi^+$	P	S	P	D	445 MeV
$\Xi^+ \to \Xi^{*0} \pi^+$	P	D	P	S	267 MeV

4. $\Xi^+ \to \Xi^{*0} \pi^+$

If the Ξ^{--} exists, then a Ξ^+ must exist as well. However, decay (4) is forbidden by $SU(3)_f$ if the Ξ^+ is in the antidecuplet. So its absence is consistent with the identification of the Ξ^{--} as the antidecuplet $\Xi^{--}_{3/2}$. The decay would not be forbidden if the Ξ^+ were in the 27_f or 35_f representation of $SU(3)_f$, so the absence of this decay supports the antidecuplet assignment of the Ξ^{--} in contrast to these other possibilities.

Presumably the dominant decays of the Ξ^+ are to $\Xi^0 \pi^+$ and $\Sigma^+ \overline{K}^0$, neither of which can be seen at NA49. Therefore discovery and study of this state must await an experiment with neutral detection capability.

The absence of a signal for the Ξ^+ via decay (4) at NA49 also supports the identification of the Ξ^- as the octet member $\Xi^-_{1/2}$. The alternative presented in (2) above was that the observed decay $\Xi^- \to \Xi^{*0} \pi^-$ is due to $SU(3)_f$ symmetry violation. But isospin symmetry alone predicts—on the antidecuplet hypothesis—that the rate for $\Xi^+ \to \Xi^{*0} \pi^+$ is 3 times larger than the rate for $\Xi^- \to \Xi^{*0} \pi^-$. Absence of this signal at the appropriate level excludes the $SU(3)_f$ violation explanation for decay (2).

B. Spin and parity

The spin and parity of the $\Theta^+(1540)$ and its partners are unknown and the subject of much speculation [1,3]. The decays (1)–(4), especially decay (2), shed some light on possible spin-parity assignments for the Ξ's. In Table I we list the lowest allowed orbital angular momentum of the two-body decay channel as a function of the initial spin and parity of the Ξ state up to $J = 3/2$. If the Ξ's have positive parity, then all the decays are P waves. The ratio of P-wave phase space for the decays to Ξ compared to Ξ^* is ≈ 4.5, which favors the decays to the Ξ when they are allowed. For this reason it is a little surprising that decay (2) has been seen. On the other hand, the relevant invariant matrix elements are unknown and might well compensate for the reduced phase space.

In contrast, the assignment $J^{\Pi}=1/2^{-}$ for the Ξ^{-} seems quite unlikely. In this case the observed decay (2) would have to be a D wave. The decays $\Xi^{-}\rightarrow\Xi^{-}\pi^{0}/\Xi^{0}\pi^{-}$ are $SU(3)_f$ allowed, have larger center-of-mass momentum, and are S wave. So NA49 would have to have seen a highly suppressed decay of the Ξ^{-}. If the observation of decay (2) by NA49 stands up, it is evidence against a $1/2^{-}$ assignment for the Ξ^{-}. The situation is reversed for $J^{\Pi}=3/2^{-}$: observation of decay (2) is more confidently expected if the Ξ^{-} has this spin-parity.

To summarize, the observation of decay (2) disfavors a $1/2^{-}$ assignment for the Ξ^{-}, is consistent with a $3/2^{-}$ assignment, and makes no strong statement about a $1/2^{+}$ or $3/2^{+}$ assignment.

IV. SUMMARY AND CONCLUSIONS

The report of cascade states around 1860 MeV by NA49 has provided rapid and striking support for the new exotic baryon spectroscopy initiated by the discovery of the $\Theta^{+}(1540)$ earlier this year. The relatively light mass of the $\Xi^{--}(1860)$ agrees with the prediction of quark dynamics based on diquark correlations. Diquark dynamics requires a baryon octet close by the exotic antidecuplet which includes the $\Theta^{+}(1540)$ and $\Xi_{3/2}^{--}(1860)$. The cascades are a particularly clean system in which to look for the octet and antidecuplet, because the octet $I=1/2$ and antidecuplet $I=3/2$ cascades are not expected to mix significantly. Remarkably, the NA49 observation of a Ξ^{-} decaying to $\Xi^{*0}\pi^{-}$ and the absence of a Ξ^{+} decaying to $\Xi^{*0}\pi^{+}$ suggest the existence of an octet cascade state nearly degenerate with the $\Xi_{3/2}^{--}(1860)$. Further experiments can test this assignment and several other aspects of our theoretical framework.

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