Light baryon resonances: Restrictions and perspectives

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(Received 27 July 2003; published 10 October 2003)

The problem of nucleon resonances N' with masses below the Δ is considered. We derive bounds for the properties of such states. Some of these are new, while others improve upon existing limits. We discuss the nature of N' states, and their unitary partners, assuming that their existence can be verified.

DOI: 10.1103/PhysRevC.68.045204 PACS number(s): 14.20.Gk, 13.30.−a, 13.75.Gx, 13.75.Cs

I. INTRODUCTION

Baryon spectroscopy continues to motivate an extensive experimental program, with most studies focused on the missing resonance problem. While many states predicted by conventional quark models have yet to be seen, other states, such as pentaquarks and hybrids, are also interesting, as they offer potentially new information on the dynamics of confinement. Given the underpopulation of conventional 3-quark states, it is difficult to identify these unconventional states. If, however, a state was to be found with a mass between the nucleon and Δ, it would undoubtedly have an exotic structure.

Such a baryon state (called here N', for brevity and according to tradition, though its isospin could be 3/2) was first suggested [1] to complete the unitary multiplet of hyperon resonance states $\Sigma(1480)$ and $\Xi(1620)$, considered now to have one-star status (see Particle Data Group (PDG) listings [2]). A baryon state in the same mass interval was later suggested as a (quasi)bound pion-nucleon state (see sources in Ref. [3]). It appeared possible, even before any specially designed experiments, to obtain bounds for the properties of such a light baryon. These bounds implied [1,3] that hadronic, and perhaps electromagnetic, couplings of the N' to usual hadrons should be small (though not necessarily forbidden), thus suggesting a narrow resonance with a small production cross section. Missing mass experiments, as well as γN interactions and electroproduction, were suggested [1] as means to search for N' states.

Direct experimental searches for N' have begun rather recently. Unfortunately, the results have been contradictory. Initially, in the reaction $pp\to nX^{++}$ at TRIUMF [4] no baryon was detected with $I=3/2, m_N\leqslant m_X\leqslant m_N+m_\pi$, and a production cross section $>10^{-7}$ of the backward elastic np cross section (an additional assumption of a long lifetime was used). However, in the reaction $pp\to p\pi^+X^0$ measured at Saclay [5] several low-mass structures were reported and interpreted as narrow peaks corresponding to new baryons.

This report renewed interest, both theoretical and experimental, in the subject. If correct, such baryons would have isospin $I=1/2$, masses of 1004, 1044, and 1094 MeV, and widths less than 4–15 MeV. Two of these could decay only radiatively, while for the third (slightly above the πN threshold) the radiative decay channel could also be important. The existence of these states was opposed in Ref. [6] on the basis of their nonobservation in the Compton scattering on protons or neutrons loosely bound in deuterons.

Similar measurements of $pd\to ppX$ at INR (Moscow) gave evidence for structures [7] interpreted by the authors as corresponding to light narrow dibaryons (see Refs. [7,8] and references therein). Simultaneously, narrow structures with $B=1$ were also observed. These could be kinematically related to the dibaryons or correspond to new narrow baryonic states with masses 966, 986, and 1003 MeV [7,8] (the latter state perhaps related to the 1004 MeV structure of Ref. [5]). However, an attempt to study one of these reported dibaryons at RCNP, Osaka, in the same reaction, but with stated better mass resolution and better background conditions, showed no statistically significant effect [9], thus possibly casting doubt on both the narrow dibaryons and baryons of Ref. [7].

Narrow light baryons have been also searched for with good precision at JLab (Hall A) and MAMI in electroproduction reactions $p(e,e'\pi^+)X$ [10,11] and $d(e,e'p)X$ [11]. No signals were found up to a missing mass of about 1100 MeV at the level 10^{-4} with respect to the height of the neutron peak.

The theoretical status of N' resonances is similarly unclear. It was noted from the beginning [1] that the smallness of N' couplings to usual hadrons "might be a consequence of the sharp difference in inner quark structure of N and N'." Since the internal spin-flavor wave function for usual octet and decuplet baryons is totally symmetric, it has been assumed that new narrow baryons have a totally antisymmetric spin-flavor wave function [12]. If so, they should not only have suppressed hadron couplings, but also forbidden one-photon decays. Such a possibility looks attractive and is frequently referred to, since it could reconcile hadron production of N' states with the absence of N' signals in Compton

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scattering and electroproduction. However, ground states (having S-wave space structure) with such spin-flavor properties should be, due to the Pauli principle, totally symmetric in color and therefore not colorless.

One explanation of the N' states hypothesized [13] the existence of a new "light pion" with a mass of about 20 MeV. New baryons were then assumed to be bound states of a usual nucleon with several light pions. However, existence of such light pions has not been confirmed in any way. Another suggestion [14] has been to construct new baryons from clusters of diquarks. The suggested mass formula produces a dense spectrum able to accomodate all the reported states and many more. Such approaches lie outside the mainstream of hadron physics, and are aimed mainly at a description of the reported mass spectrum of the narrow baryons.

Our renewed investigation of the N' puzzle has been partly motivated by a recent set of measurements, suggesting that unconventional multiquark systems may indeed exist in nature. Experimental evidence from SPring-8, ITEP, JLab, and ELSA measurements [15–19] suggests the existence of an exotic Θ^+ baryon (former Z^+). Predicted [20] on the basis of the chiral soliton model, it has positive strangeness and, therefore, is exotic, i.e., cannot consist of only three quarks. If exotic hadrons really do exist, some could have the same quantum numbers as nucleons. The chiral soliton approach for Θ^+ and its relatives [members of the same $SU(3)_F$ multiplet] predicts that they will have $J^P=1/2^+$, which requires, for the $(4q)\overline{q}$-system, at least one orbital excitation (P wave). Therefore, one may expect the existence of lower-lying nucleon and other baryon states. We will return to this suggestion later on.

Our presentation proceeds as follows. In Sec. II, we first consider various new restrictions for the existence of N' states, separately below and above the πN threshold, and discuss how they are related. Then, in Sec. III, we discuss the possibility of N' being a candidate for a 5-quark system. We also give a tentative description of the unitary partners of N'. The whole picture is summarized in the Conclusion.

II. BOUNDS ON N' PROPERTIES

Having controversial results from dedicated experiments searching for N', we first study what limitations can be obtained at present from other considerations. This will allow us to check for consistency in the present status of possible light nucleon resonances. It is convenient, at this point, to consider separately the cases of N' states above or below the πN threshold.

A. Elastic resonances

If we assume that the new state N' exists above the elastic πN threshold, but below the $\Delta(1232)$, it is then natural to expect that N' decays only (or, at least, mainly) to πN. In this case, one might expect a partial-wave analysis to easily reveal the presence or absence of such a resonance. This is, however, not quite so.

There are two kinds of partial-wave analyses (PWA's): single-energy (SE), when a PWA is made independently in narrow energy bins, and energy-dependent (ED), which uses an energy-dependent parametrization to consider simultaneously data at various energies. In the SE treatment, one can miss a resonance which is narrow enough to fall into the gap between two neighboring energy bins. The ED consideration assumes a mild energy dependence, and may smear a narrow resonance peak down to (nearly) zero. Consequently, we must use another approach to search for narrow elastic resonances.

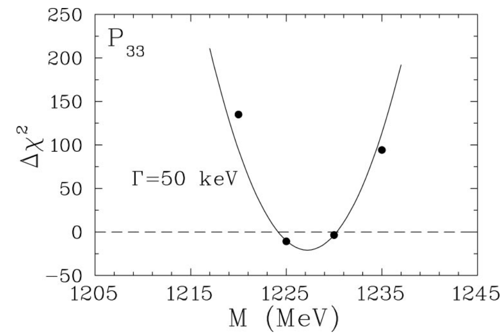

FIG. 1. Change of overall χ^2 due to insertion of a resonance into P_{33} for M=1100–1295 MeV and Γ=50 keV, using πN PWA [22]. The curve is given to guide the eye.

We have used the πN SAID database, which is the basis for SE and ED PWA's [21]. The existence of a resonance was then assumed in a particular partial-wave amplitude (i.e., with fixed quantum numbers), having fixed values of mass and width. With this addition, we have readjusted all other fitting parameters to minimize χ^2. If a resonance is actually present, we expect that the fit should improve (lowering χ^2) once it is included.

We applied this procedure for pion laboratory energies below 500 MeV, adding resonances to all S waves, all P waves, and two D waves: S_{11},S_{31},P_{11},P_{13},P_{31},P_{33},D_{13}, and D_{15}. Other partial-wave amplitudes are very small in the considered energy interval and can be neglected. For trial masses, we use values from 1100 MeV up to 1300 MeV (formally, we enter the inelastic region, but the inelasticity is very small). For widths, we take 50, 100, 150, 200, 250, and 300 keV (additional resonances with higher widths are definitely excluded).

Surveying our results, we found a case where it was possible to diminish χ^2. This could be done by inserting a resonance with a mass of 1225 MeV and a width of 50 keV into the wave P_{33} (see Fig. 1). The change of χ^2 reaches −11, while χ^2 itself is about 6000. To reveal the nature of this effect, we note that the "suspected" mass value appears very near the $\pi\pi N$ threshold which is 1220 MeV. This threshold is accounted for in the parametrization of partial-wave amplitudes, but not exactly. Insertion of a narrow "resonance" imitates small corrections to the threshold description. Such an interpretation is supported by the fact that $\Delta\chi^2$ as a function of the trial resonance mass has the local minima near 1220 MeV for any resonating partial wave and for any assumed resonance width (see, e.g., Fig. 2).

One more interesting effect emerges in the wave S_{11} for the resonance width Γ=50 keV. This generates a sharp minimum for $\Delta\chi^2$ at the assumed resonance mass 1145 MeV

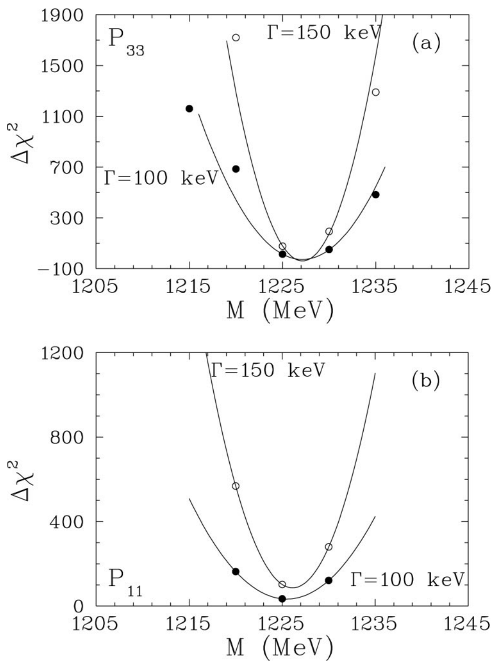

FIG. 2. Change of overall χ^2 due to insertion of a resonance into (a) P_{33} and (b) P_{11} for M=1100–1295 MeV and Γ=100 and 150 keV, using πN PWA [22]. The curves are given to guide the eye.

(which corresponds to a pion kinetic energy of 79.5 MeV in the laboratory frame). Though $\Delta\chi^2$ stays positive here, it takes a very small value, about 9 (Fig. 3). No threshold is present at this mass and, to clarify the case, we have examined the experimental data in this region. It appears that there is a gap in data, which could be "filled" by a narrow resonance (with a width smaller than 50 keV). Its presence would dramatically change cross sections and polarization effects of πN interactions in the resonance region as compared to the present nonresonant expectations (see Fig. 4) but would have practically no effect on the existing data (Fig. 5). Interestingly, this gap in data also allows local minima of $\Delta\chi^2$ near 1145 MeV for any partial wave and for each (small enough) trial resonance width. This situation demonstrates the limited sensitivity of existing data to the resonance problem. Indeed, sufficiently narrow resonances (with $\Gamma < 50$ keV

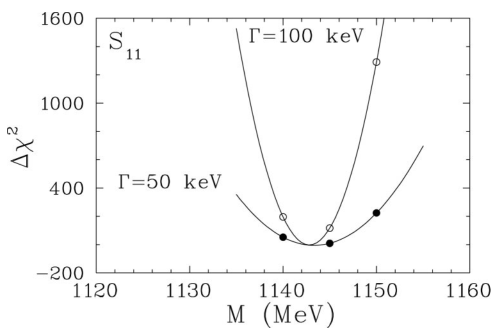

FIG. 3. Change of overall χ^2 due to insertion of a resonance into S_{11} for M=1100–1295 MeV and Γ=50 and 100 keV, using πN PWA [22]. The curves are given to guide the eye.

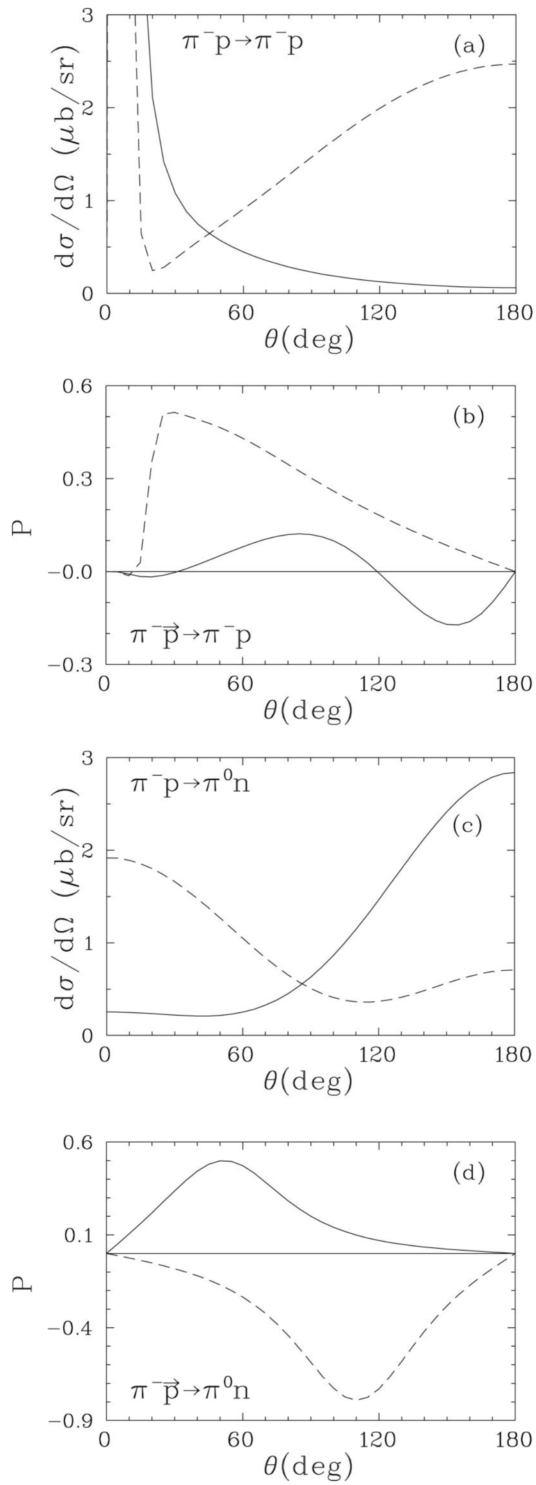

FIG. 4. Differential cross sections (a,c) and polarization parameter P (b,d) for $\pi^- p \to \pi^- p$ (a,b) and $\pi^- p \to \pi^0 n$ (c,d) at T_π =79.5 MeV. The solid (dotted) line plots the SAID solution [22] (plus the S_{11} resonance at M=1145 MeV and Γ=50 keV).

for the present data) can always be inserted into one or another partial wave providing a better fit even if a true resonance is absent there.

Our considerations allow us to draw some conclusions, as follows.

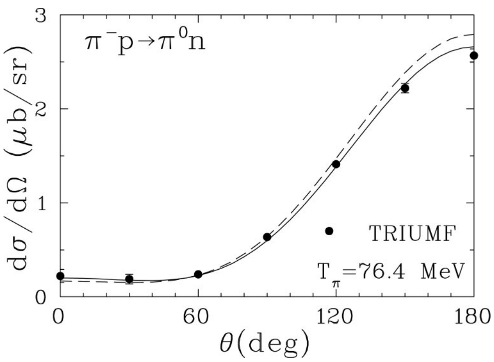

FIG. 5. Differential cross section for $\pi^- p \to \pi^0 n$ at $T_\pi = 76.4$ MeV. The solid (dotted) line plots the SAID solution [22] (plus the S_{11} resonance at $M=1145$ MeV and $\Gamma=50$ keV). Experimental data at $T_\pi=76.4$ MeV are from TRIUMF [23].

(1) We find no evidence for elastic πN resonances in the region between the πN threshold and 1300 MeV having a width $\Gamma \geqslant 50$ keV.

(2) The present πN data cannot exclude even purely elastic (or inelastic) narrow resonances with widths below 50 keV.

(3) Insertion of trial narrow resonances may be a good "technical trick" to check the quality of fit to a set of experimental data.

To estimate the meaning of the obtained results for additional resonance(s), let us compare them to the well-known properties of the $\Delta(1232)$, having a width of about 120 MeV. Thus, we have

$$\Gamma(N') < 50 \text{ keV}, \qquad \Gamma(N')/\Gamma(\Delta) < 4 \times 10^{-4}. \qquad (1)$$

Up to now, we have discussed only the hadronic interactions of N'. However, such a narrow resonance could have a significant radiative decay $N' \to N\gamma$. If so, it should produce a signal in the Compton γN scattering, proportional to $\mathrm{Br}_\gamma^2(N')\Gamma_{N'}$. Absence of the signal in the γp data up to $E_\gamma = 290$ MeV [24] allowed the derivation of a limit [6] which depends on the assumed mass of N'. For the whole region $m_N < m_{N'} < 1200$ MeV, it gives

$$\mathrm{Br}_\gamma^2(N')\Gamma_{N'} < 10 \text{ eV}. \qquad (2)$$

For comparison, $\mathrm{Br}_\gamma^2(\Delta)\Gamma_\Delta = 3.6$ keV [2]. Thus, if the N' does exist between the πN threshold and the Δ region, the Compton data require a suppression

$$\frac{\mathrm{Br}_\gamma^2(N')\Gamma_{N'}}{\mathrm{Br}_\gamma^2(\Delta)\Gamma_\Delta} < 2.8 \times 10^{-3}, \qquad (3)$$

an order of magnitude weaker than the result of Eq. (1) for total widths.

B. Subthreshold states

We next consider N' states below the πN threshold. Of course, such states cannot decay to πN and cannot be seen as a resonance in πN scattering. They may be, nevertheless, coupled to the πN channel. Then, as was suggested earlier [1,3], the πN scattering data may give useful information about the N' through dispersion relations (DR). These relations for the $\pi^- p$ amplitude contain a contribution from the neutron pole at the unphysical value $s = m_n^2$ (s is the squared πN energy in the center-of-mass frame), with a residue proportional to $g_{\pi NN}^2$. The $\pi^+ p$ amplitude does not contain such a pole, since there are no stable baryons with $I=3/2$, but has the neutron pole in the crossed channel, at the unphysical point $u = m_n^2$ (u being the squared four-momentum transfer from proton to π^+, again, in the center-of-mass frame). These properties underlie the use of DR to extract $g_{\pi NN}^2$ from experimental πN scattering data (for a description of the procedure, see Ref. [25]).

If N' does exist with $m_{N'} < m_N + m_\pi$ and couples to the πN system, it generates an additional pole in the πN scattering amplitude. For simplicity, let us assume here that N' has the same quantum numbers as the nucleon ($I=3/2$ is excluded with high precision by the data [4]; spin and/or parity of N' different from N would only provide an additional factor, of order unity, in the residue). The procedure of Ref. [25] for such a case is really sensitive only to the sum $g_{\pi NN}^2 + g_{\pi NN'}^2$ and cannot separate the two terms. Therefore, we should rewrite the result based on the use of DR [22] as

$$(g_{\pi NN}^2 + g_{\pi NN'}^2)/(4\pi) = 13.76 \pm 0.05. \qquad (4)$$

There is, however, an alternative way to extract $g_{\pi NN}^2$ from the pion exchange contribution to NN scattering. This is not spoiled by the presence of N'. A consistency requirement of the two methods can help in extracting or restrict $g_{\pi NN'}^2$. In this way, np scattering gives [26]

$$g_{\pi NN}^2/(4\pi) = 13.69 \pm 0.09. \qquad (5)$$

Thus, $g_{\pi NN'}^2/(4\pi)$ should not be more than, say, 0.14, i.e.,

$$g_{\pi NN'}^2/g_{\pi NN}^2 \leqslant 10^{-2}. \qquad (6)$$

Note that an earlier bound of this kind was weaker, with a limit of 0.1 [1,3]. One should note, however, that the uncertainty in Eq. (5) could be larger [27].

A somewhat different method to restrict $g_{\pi NN'}^2$ was suggested in Ref. [3]. This was based on the Adler-Weisberger (AW) sum rule [28,29] related to the algebra of currents. In contrast with the DR method, the employed current algebra is not rigorously derived for strong interactions. It can only be an approximation requiring, in particular, the pion to be massless, without a systematic method for corrections. Specifically for the AW sum rule, Adler has discussed possible corrections, estimating the likely error to be about 5% [29]. Therefore, methods based on the AW sum rule cannot give more reliable bounds than DR, and we do not use them here.

As in the preceding section, we continue by considering processes including other interactions, which could be useful in the search for N' states. One of these is the capture of stopped pions.

Negative pions, being stopped in hydrogen, produce mainly two final states:

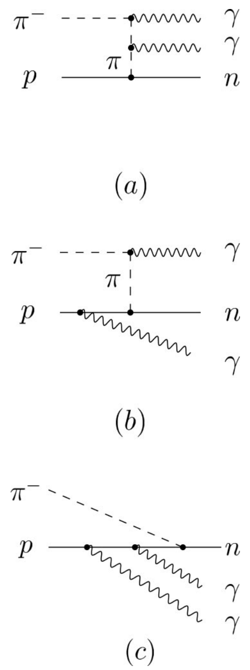

FIG. 6. Diagrams for the direct $n2\gamma$ production in $\pi^- p$ capture.

$$\pi^- p \to n\pi^0, \qquad \pi^- p \to n\gamma. \tag{7}$$

Their relative abundance is described by the Panofsky ratio $R = W(n\pi^0)/W(n\gamma)$ which is about 1.5.

The pion final state provides the best system for a precise determination of the pion mass difference through accurate measurements of either the neutron velocity or that of the neutral pion. The former can be measured by the time of flight (TOF), while the latter can be found from $\gamma\gamma$ angular correlations in the final state $n2\gamma$ that emerges after the π^0 decay. The same final state, but with a different angular distribution, appears due to the direct two-photon process $\pi^- p \to n2\gamma$ (see diagrams of Fig. 6).

An n' state with mass between m_n and $m_p + m_{\pi^-}$ provides one more source for the $n2\gamma$ final state:

$$\pi^- p \to n'\gamma \to n\gamma\gamma \tag{8}$$

(compare diagrams of Fig. 7). Therefore, a detailed investigation of this 2γ final state may provide further evidence for, or a restriction on, n' contributions.

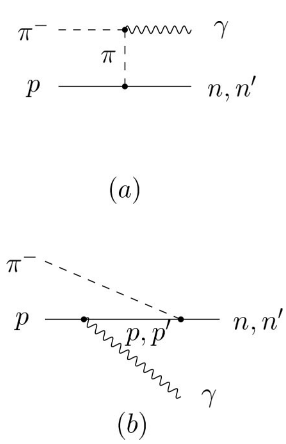

FIG. 7. Diagrams for the radiative capture of $\pi^- p$.

The most precise measurement of the pion mass difference comes today from the TOF experiment at PSI [30], with a nearly discrete neutron velocity corresponding to the $n\pi^0$ final state. One more discrete neutron velocity, for the $n\gamma$ final state, is also seen quite well. The direct transition to $n2\gamma$ and/or the n' cascade would produce signals with different properties: they should have continuous velocity distributions. Unfortunately, such signals in the work [30], if they exist, seem to be subtracted together with background.

Another approach was used in a TRIUMF measurement [31]. The authors have studied the final $n2\gamma$ system in the kinematical configuration which totally excluded contributions from the $n\pi^0$ final state. They were thus able to find the signal for direct $n2\gamma$ decay. Assuming theoretically expected energy-angle distributions, the measured branching ratio for $\pi^- p \to n2\gamma$ was $[3.05 \pm 0.27(\text{stat}) \pm 0.31(\text{syst})] \times 10^{-5}$ [31].

Important for our goal here is the fact that the measured $\gamma\gamma$ distributions show reasonable agreement with theoretical calculations for the direct 2γ decay. This means that up to statistical and systematic uncertainties (each about 10%) there were no contributions of the n' cascade. Keeping in mind the incomplete kinematical coverage and the different energy-angle distributions for direct and cascade decays (the latter depending also on the spin-parity of n'), we can safely use the measured intensity of the direct decay as an upper bound for the cascade decay. Then, accounting for the Panofsky ratio and assuming a 100% branching ratio for $n' \to n\gamma$, we derive the conservative estimate

$$\frac{W(\pi^- p \to n'\gamma)}{W(\pi^- p \to n\gamma)} < 8 \times 10^{-5} [\sim 10^{-5}]. \tag{9}$$

The number in the square parentheses corresponds to the assumption that contribution of the N' cascade is smaller than the total experimental uncertainty of the direct decay signal. Again, note that earlier data on the π^- capture allowed only a weaker result for this bound, 10^{-3} [1].

Coupling of N' to the $N\gamma$ channel should generate a contribution to the Compton scattering. Since it has not been seen for proton or neutron targets, one obtains a mass-dependent bound for the radiative widths [6]. For the whole interval from m_N up to the πN threshold, it is

$$\Gamma(N' \to N\gamma) < 5 \text{ eV}, \tag{10}$$

while at the lower end of the interval it can be a fraction of an eV. In terms of dipole moments and their effective lengths this leads to values which can be three orders of magnitude smaller than the size of the nucleon [6]. Of course, $\Gamma(N' \to N\gamma)$ in the discussed mass region is just the total width $\Gamma_{N'}$ if this decay mode is not suppressed somehow. If, however, the $N\gamma$ mode is essentially suppressed, it might become comparable to the $N\gamma\gamma$ mode.

C. Interpretation of bounds for N'

Let us summarize and compare existing bounds for various quantities describing interactions (or couplings) of the N' with familiar hadrons. Results of both the previous sections

TABLE I. Bounds for N' properties.

Interactions	Below πN threshold	Above πN threshold
Purely Hadronic	$\frac{g^2_{\pi NN'}}{g^2_{\pi NN}}<10^{-2}$	$\Gamma_{N'}<50$ keV
	$\frac{\sigma(pp\to nX^{++})}{\sigma(pn\to np)}<10^{-7}$ [4]	$\left[\frac{\Gamma_{N'}}{\Gamma_\Delta}<4\times10^{-4}\right]$
	$\frac{\sigma(pp\to\pi^+pX^0)}{\sigma(pp\to\pi^+pn)}\sim10^{-3}-10^{-4}$ [32]	
Hadronic and EM	$\frac{W(\pi^-p\to n'\gamma)}{W(\pi^-p\to n\gamma)}<8\times10^{-5}[\sim10^{-5}]$	
	$\Gamma_{N'\to N\gamma}<5$ eV [6]	$\mathrm{Br}_2^\gamma\,\Gamma_{p'}<10$ eV [6]
	$\frac{Y(ep\to e'\pi^+X^0)}{Y(ep\to e'\pi^+n)}<10^{-4}$ [10,11]	$\left[\frac{Br_\gamma\,\Gamma_{p'}}{Br_\gamma\Gamma_\Delta}<2.8\times10^{-3}\right]$
	$\frac{Y(ed\to e'pX^0)}{Y(ed\to e'pn)}<10^{-4}$ [11]	

and other works are compiled in Table I. At first sight, they cannot even be compared to each other, since they concern different kinds of interactions and processes. However, all these bounds are interrelated, at least, "parametrically."

To begin with, we consider first the case of an N' below the πN threshold. States with $I=3/2$ are strongly excluded here by the TRIUMF experiment [4]. Keep in mind, however, that this strong bound is applicable only if the double-charged member of the isotopic quartet is very long lived, having $\tau\geqslant10^{-2}$ sec; for shorter lifetimes it becomes weaker. The bound is about 10^{-6}, instead of 10^{-7}, for $\tau\approx25$ nsec and rapidly weakens for smaller τ.

For $I=1/2$, the most strict limitation in Table I seems to be the bound for $\pi^-p\to n'\gamma$ compared to $n\gamma$. It is in good correspondence with limits from Compton scattering, also strict. Indeed, using a suppression factor, say, $5\cdot10^{-5}$ we can estimate an upper bound for the radiative width of N' as a function of its mass:

$$\Gamma_\gamma(N')<5\cdot10^{-5}\Gamma_\gamma(\Delta)\left(\frac{m_{N'}-m_N}{m_\Delta-m_N}\right)^3. \qquad (11)$$

For masses 1004, 1044, and 1094 MeV this gives 0.3, 1.5, and 4 eV, respectively, as upper bounds of $\Gamma_\gamma(N')$, while direct treatment [6] of the Compton data provides in the same cases 0.2, 1.6, and 7 eV.

At first sight, one cannot directly compare estimates from π^- capture to the bound for $g^2_{\pi NN'}$ from DR, because they relate to different kinds of interactions. However, let us consider the structure of the corresponding amplitudes. Contributions to the radiative capture of the pion come from the diagrams such as those of Fig. 7. The main ones are the pion exchange [Fig. 7(a)], proportional to $g_{\pi NN'}$ or $g_{\pi NN}$ in the amplitudes and to $g^2_{\pi NN'}$ or $g^2_{\pi NN}$ in the capture probabilities. This illustrates that, if the capture to $N'\gamma$ has no special kinematical suppression (e.g., for $m_{N'}$ very close to $m_{\pi^-}+m_p$), then the radiative pion-capture limitation of Eq. (9) requires a stronger suppression of the purely hadronic N' couplings. In particular,

$$\frac{g^2_{\pi NN'}}{g^2_{\pi NN}}<10^{-4}[10^{-5}], \qquad (12)$$

where the number in the square parentheses has the same meaning as in Eq. (9). Note that DR could provide only the weaker bound of Eq. (6) because of insufficient precision of the set of πN and NN scattering data.

Thus, $g_{\pi NN'}$ should be not more than $10^{-2}g_{\pi NN}$. The presence of the non-pion-exchange contribution of Fig. 7(b), without strong vertex suppression, requires the radiative vertex $\gamma NN'$ to be also suppressed, in comparison with γNN, at least by the same factor 10^{-2}. Moreover, Compton data show that in some cases the radiative vertex may be suppressed even stronger by the factor of 10^{-3} [6]. The situation for the case of $m_{N'}>m_N+m_\pi$ looks similar.

We can make the self-consistent assumption that in all cases both strong and electromagnetic couplings of N' with usual hadrons should be suppressed more strongly than by a factor of 10^{-2} in amplitudes.

As a result, we expect that if the light resonances do exist, their hadroproduction, photoproduction, and electroproduction can be seen only at a level smaller than 10^{-4} with respect to "normal" cross sections for usual hadrons. We also note in passing that for $m_{N'}<m_N+m_\pi$ the hadroproduction of N' could appear as a special contribution to bremsstrahlung, e.g., $NN\to NN'\to NN\gamma$.

III. POSSIBLE NATURE OF N'

The bounds for N' properties, discussed above, appear rather severe and may be considered as evidence against the existence of such states. If, nevertheless, there are arguments for their existence, one needs to have an explanation for why couplings to usual hadrons are so suppressed.

In the Introduction, we briefly mentioned a motivation for considering nonstandard quark states, based on the recently reported baryon Θ^+ [15–19] with clearly exotic quantum numbers. Being identified on the basis of rather low statistics, further confirmation is necessary. However, if it does exist, it poses questions for hadrons with nonexotic quantum numbers as well. Here, we discuss Θ^+ and its possible relation to the N' problem in more detail.

Θ^+ has strangeness $S=+1$ and, being considered as a quark system, should contain at least four nonstrange quarks and one strange antiquark. Its experimental mass agrees very well with a theoretical prediction [20]. This gives some hope that its spin and parity also correspond to the predicted values $J^P=1/2^+$. However, the product of internal parities of four quarks and one antiquark is negative. Therefore, the space wave function of Θ^+ cannot be pure S wave; it should contain at least one P wave to make the total parity be positive.

In quantum theory (at least, nonrelativistic) there exists a mathematically exact result that the space wave function of the ground (lowest-energy) state should not have zeros. Since the P-wave Schrödinger function inevitably has at least one zero, the ground-state character of Θ^+ may be questionable. Of course relativistic theory has some specifics, and there are recent statements [33] that in the particular case of the quark structure of Θ^+, the hyperfine interaction may reverse the normal order of the lowest S- and P-wave states. However, the flavor dependence of such interaction prevents this property from being universal for all members of the $SU(3)_F$ antidecuplet which contains Θ^+. Therefore, if the nonstrange partner of Θ^+ is indeed $N(1710)$, as assumed from Ref. [20], we can expect that it is not a ground state.

Dynamics of the 5-quark system may be rather unfamiliar. Nevertheless, having nothing better at present, we can try to use 3-quark experience for a tentative estimate of the energetic "price" of a P wave in a system with nucleon flavor quantum numbers.

The ground state for baryons with $S=0$ and $I=1/2$ is $N(940)$ with $J^P=1/2^+$. It corresponds to the 3-quark system having the pure S-wave space function and sum of the spins equal 1/2. If we consider the corresponding excited system with one P wave, we obtain two states with $J^P=1/2^-$ and $3/2^-$ having different masses due to (LS) coupling. Particle tables [2] show that the lowest states with such quantum numbers are $N(1520)$, with $J^P=3/2^-$, and $N(1535)$, with $J^P=1/2^-$, both having the highest four-star status. We see, therefore, that the (LS) coupling is relatively weak, while the P-wave excitation requires about 600 MeV.

Near $N(1710)$, with $J^P=1/2^+$ and three-star status, we find $N(1720)$, with $J^P=3/2^+$ and four-star status. If they both are 5-quark systems with one P wave, having the same energetic price of about 600 MeV, we expect that the corresponding

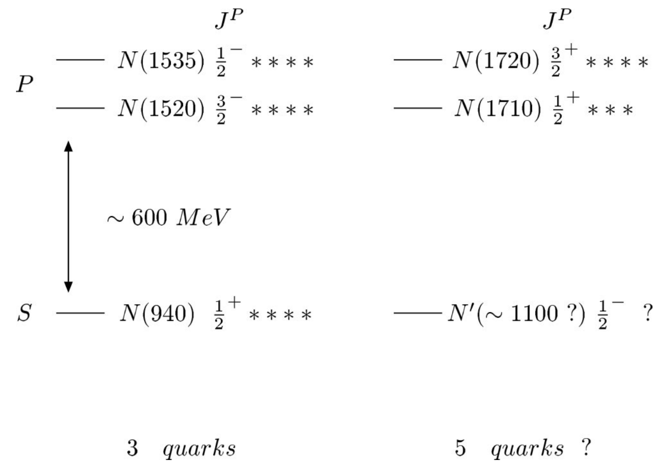

FIG. 8. Possible S- and P-wave levels in quark systems.

ground state should have mass about 1100 MeV. Thus, it is just the mass region near the πN threshold where appearance of an N' is expected. The situation is schematically shown in Fig. 8. By analogy with usual hadrons, we show quantum numbers of N' as $J^P=1/2^-$. However, the 5-quark system is, of course, complicated enough, and may manifest several states with nearby masses, having different values of J^P.

A. Problem of suppressed couplings

So far the picture of an N' as a 5-quark state looks sufficiently consistent. But, as we explained above, to support it, we should demonstrate that such a picture has the ability to describe the phenomenologically necessary suppression of couplings of N' with usual 3-quark baryons.

Dynamics of the 5-quark system may be essentially different from that of the 3-quark system. Even the constituent-quark mass, being a dynamical quantity, might be different for these two cases (most probably, it decreases with increasing the quark number). That is why we will not pretend here to give a reliable description of coupling constants for the 5-quark hadrons. However, we can recall some known phenomena which may provide a realistic basis to describe the suppression of couplings.

At first sight, the 5-quark baryon can be easily separated into a usual baryon (three quarks) and a usual meson (quark and antiquark). But this may be difficult because of inappropriate color structure. In this connection, let us recall the color suppression, well known in weak decays (especially, of heavy-quark mesons).

Figure 9 shows two kinds of contributions for weak decays. In both cases, the W boson produces the colorless quark-antiquark pair. In one case [Fig. 9(a)], the pair directly transforms into a meson (e.g., π meson), without any problem. In the other case [Fig. 9(b)], the quark and antiquark, separately, produce hadrons together with other quarks and antiquarks of the system. Not all color configurations of the pair are appropriate for the second process, so its amplitude contains the factor $1/N_c$ and its probability contains $1/N_c^2$, where N_c is the number of colors. Thus, at $N_c=3$ such simple "color suppression," even in decays of "normal" hadrons, provides a factor of about 1/10 for the probability of the "suppressed" final state.

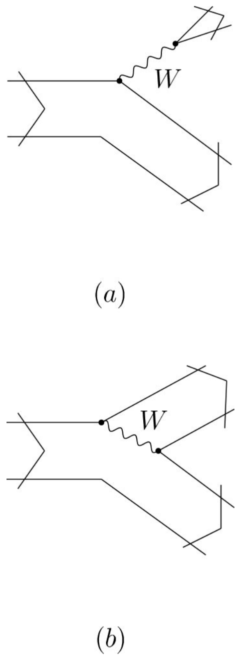

FIG. 9. Decay diagrams without/with color suppression.

The increased number of quarks in the system should increase the number of possible inconsistencies in its color structures, which suppress decays of the system. Double color suppression by itself would give the suppressing factor of 10^{-1} for the strong coupling between a 5-quark baryon and, say, the baryon-meson pair of usual octet hadrons. Together with similar inconsistencies of the flavor and spin parts of the wave function, it may be not so hard to provide a suppression of 10^{-2} for the coupling constants of N', i.e., 10^{-4} for processes of its production.

If the color and spin-flavor structures of the 5-quark baryon are indeed capable of producing a suppression of 10^{-2} or more for strong couplings of the 5-quark baryon, they should give, at least, the same suppression for the photon vertex of such a baryon. However, as we discussed in the preceding section, the phenomenological photon vertex may even need stronger suppression, at least, 10^{-3}. Let us consider whether this could be realistic.

In the framework of the constituent quark model, the diagonal and transition dipole moments (say, magnetic moments) for usual (octet and decuplet) baryons can be well described as simple matrix elements of the single-quark electromagnetic interaction between quark wave functions of the initial and final baryons. But such a simple approach cannot work for the photon transition between 5- and 3-quark baryons because of the different number of quarks. This vertex should have a more complicated structure, e.g., that of Fig. 10(a). It evidently contains the suppression of strong couplings, but its loop configuration may provide additional suppression, similar to the so-called "penguin" diagrams of Fig. 10(b) in weak processes. These diagrams do not have parametric smallness with respect to usual weak amplitudes, but are known to be numerically small.

The existence of diagrams such as Fig. 10(a) shows that the one-photon transition between N' and N may be suppressed, but cannot be forbidden entirely, contrary to the suggestion of Ref. [12]. In such a situation, an interesting question arises as to whether the suppressed probability of the one-photon decay for N' might become numerically of the same order as the probability of the two-photon decay.

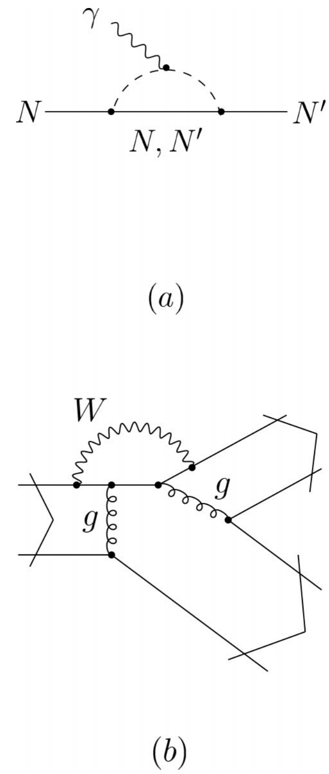

FIG. 10. Loop diagram contributions to decay vertices. (a) Diagram for $N'N\gamma$. (b) Penguin diagram for weak decay.

B. Unitary partners of N'

With the existence of an N' there inevitably emerge additional problems, related to the $SU(3)_F$ symmetry. What is its unitary multiplet? What are its unitary partners?

Both questions require detailed investigation which will be given elsewhere. For now, we restrict ourselves to the simplest hypothesis of N' being a member of a unitary octet, and tentatively discuss other possible members of this octet (Fig. 11).

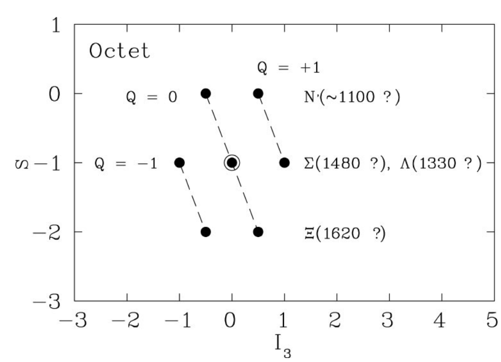

FIG. 11. Tentative unitary octet with N'.

TABLE II. Possible unitary octet with N'.

State	Mass (MeV)	Width (MeV)	Decay modes	Hadron production cross sections
N'	$\sim$1100	$<$0.05	$N\gamma$	$<10^{-4}$ of normal
Λ	1330		$\Lambda\gamma$	$\sim$10 μb
Σ	1480	30–80	$\Lambda\pi, \Sigma\pi, N\overline{K}$	$\sim$1 μb
Ξ	1630	20–50	$\Xi\pi$	$\sim$1 μb

Two of the potential candidates appear to be present in the PDG listings [2]. They are $\Sigma(1480)$ and $\Xi(1620)$, both with low one-star status. One more multiplet member might be the resonance $\Lambda(1330)$ observed as a peak in the system $\Lambda\gamma$ [34].

All these states were observed in experiments with bubble chambers, and have been nearly forgotten with the coming of a new generation of detectors and facilities (and also new energy regions). The latest publications are Refs. [35,36] on $\Sigma(1480)$ and [37,38] on $\Xi(1620)$.

Recently they have begun to reappear. $\Sigma(1480)$ is seen in very preliminary data of COSY [39], weak evidence for $\Lambda(1330)$ may be seen in a low statistics preliminary study of the $\Lambda\gamma$ spectrum at JLab (Hall B) [40]. $\Xi(1620)$ has recently emerged in theoretical calculations of $\Xi\pi$ scattering in the framework of a unitary extension of chiral perturbation theory [41,42]. Interestingly, these calculations assign $J^P=1/2^-$ for $\Xi(1620)$, exactly as we suggested above for N'. Moreover, the Gell-Mann-Okubo mass formula with masses of $\Lambda(1330)$, $\Sigma(1480)$, and $\Xi(1620)$ gives for N' just the mass of about 1100 MeV [1], in agreement with the estimation above, based on different arguments. Present information on this tentative unitary octet is summarized in Table II. It shows, in particular, reported decay modes and values of hadronic production cross sections. Note that the corresponding cross sections for photoproduction may be estimated as multiplied by the factor α/π, while for electroproduction, the factor should be of the order of $(\alpha/\pi)^2$.

Of course, the experimental status of all these states is quite uncertain. Publications, which report their observation, estimate their statistical significance at the 3, or even 4, standard deviation level [for $\Sigma(1480)$ both the peak in the mass distribution and the polarization effect were reported [35]]. Many papers, which do not support those states, actually see the corresponding peaks, but cannot exclude their nonresonant origin (background fluctuations, kinematical reflections, and so on). Therefore, the problem should be further investigated at the modern level of accuracy.

IV. CONCLUSION AND DISCUSSION

The recent discovery of Θ^+ [15–19] (of course, being reliably confirmed) may open a new vista on the field of many-quark hadrons. Their dynamics, though also based on QCD, can be phenomenologically different from the familiar strong interactions of the standard 3-quark and quark-antiquark hadrons. Among other opening possibilities, there could (or even should) exist new light nonstrange baryon(s), with mass(es) near N and Δ.

In this paper, we have studied the present bounds on properties of the hypothetical light baryon(s) N'. Together with the dedicated experiments searching for N', we also consider other data, not obviously directly related to N'. Using these, we are able to enhance previous bounds, and obtain new ones, for both strong and electromagnetic couplings of the N'.

While Δ-like baryons (with $I=3/2$) below the πN threshold are strongly excluded at the level of 10^{-7} [4], it is not so for N-like states (with $I=1/2$) in the same mass region. Here, we show that all couplings of N' to the standard hadrons should be suppressed more strongly than a factor of 10^{-2}. This implies small (radiative) decay widths and small production cross sections (less than 10^{-4} or even 10^{-5} with respect to analogous production of standard hadrons). Above the πN threshold and up to the Δ region, we obtain new restrictions for couplings of both $I=1/2$ and $3/2$ nonstrange baryons, again at a level stronger than 10^{-4}. Though the 5-quark systems and their dynamics are complicated and insufficiently understood, we give arguments that the necessary phenomenological suppression may be realistic.

We have also briefly discussed unitary multiplets possibly related to N' and 5-quark systems. They could be both familiar octets and decuplets, and also clearly exotic antidecuplets or even 27 plet(s) (note that Δ-like states do not appear in octets and/or antidecuplets). We have recalled some nearly forgotten states which could appear as unitary partners of N'. Studies of such partners might give an alternative view of the problem of N'. It is interesting in this connection that the reported cross sections for hadronic production of those states (of the order of several microbarns, see Table II) are consistent with rough estimates of several nanobarns for photoproduction of Θ^+ [43] (the relative factor of α/π).

The problem of N' may have even broader interest than just hadron physics. For instance, it was demonstrated recently that existence of N' may influence properties of neutron stars [44] and diminish their mass. Since this result was used by the authors as an argument against the existence of N' (the calculated limiting mass of the neutron star appears lower than the experimental value), we would like to note that similar problems might arise also due to (well established) hyperons. They, however, may be eliminated by other effects, such as rotation excitations, repulsive potentials, and other effects [45], which were not accounted for in Ref. [44].

ACKNOWLEDGMENTS

One of the authors (Ya.A.) highly appreciates the hospitality extended to him by the Jefferson Lab. The authors acknowledge useful communications with W.J. Briscoe, X. Jiang, V. Koubarovsky, M. Kovash, E. Pasyuk, G. Pavlov, M. Polyakov, W. Roberts, and B. Wojtsekhowski. This work was supported in part by the U.S. Department of Energy under Grant DE–FG02–99ER41110 and Russian State Grant No. SS–1124.2003.2. The authors acknowledge partial support from Jefferson Lab, by the Southeastern Universities Research Association under DOE Contract No. DE–AC05–84ER40150.

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