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Chiral multiplets versus parity doublets in highly excited baryons

Thomas D. Cohen
Department of Physics, University of Maryland, College Park, Maryland 20742-4111

Leonid Ya. Glozman
Institue for Theoretical Physics, University of Graz, Universitätsplatz 5, A-8010 Graz, Austria

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It has recently been suggested that the parity doublet structure seen in the spectrum of highly excited baryons may be due to effective chiral restoration for these states. We argue how the idea of chiral symmetry restoration high in the spectrum is consistent with the concept of quark-hadron duality. If chiral symmetry is effectively restored for highly lying states, then the baryons should fall into representations of $SU(2)_L \times SU(2)_R$ that are compatible with the given parity of the states—the parity-chiral multiplets. We classify all possible parity-chiral multiplets: (i) $(1/2,0)\oplus(0,1/2)$ that contain parity doublet for nucleon spectrum, (ii) $(3/2,0)\oplus(0,3/2)$ consists of the parity doublet for delta spectrum, (iii) $(1/2,1)\oplus(1,1/2)$ contains one parity doublet in the nucleon spectrum and one parity doublet in the delta spectrum of the same spins that are degenerate in mass. Here we show that the available spectroscopic data for nonstrange baryons in the ~ 2 GeV range are consistent with all possibilities, but the approximate degeneracy of parity doublets in nucleon and delta spectra support the latter possibility with excited baryons approximately falling into $(1/2,1)\oplus(1,1/2)$ representation of $SU(2)_L \times SU(2)_R$ with approximate degeneracy between positive and negative parity N and Δ resonances of the same spin.

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I. INTRODUCTION

It is believed that ultimately QCD, the underlying theory of the strong interaction, can explain all of the features of hadronic physics. However, the subject remains of considerable importance since predictions of hadronic phenomena from QCD remains computationally intractable for many problems despite advances made in lattice gauge theory. Moreover, the manner that the underlying QCD degrees of freedom transmute into the observable hadronic degrees of freedom is subtle and complex and of great intellectual interest. One interesting feature of hadronic physics is the appearance of approximate parity doublets for highly excited baryons (baryons with a mass of ~ 2 GeV and above). Recently it has been suggested that these parity doublets can be explained by an effective restoration of chiral symmetry for these highly excited states [1].

One feature of QCD that is well understood is that the theory possesses an approximate $SU(2)_L \times SU(2)_R$ symmetry (which becomes exact as the current quark mass goes to zero) and that this symmetry is spontaneously broken. Clearly, in the absence of both explicit and spontaneous symmetry breaking all hadronic states would fall into chiral multiplets and each multiplet would have both positive and negative parity states. For example, in the meson sector the mass difference between the positive parity σ and the negative parity π is entirely due to chiral symmetry breaking. One possible way to understand the near degeneracy between highly excited baryons of different parities is to suggest that for states in this regime there is some type of effective chiral symmetry restoration. Although this has been referred to as a phase transition [1] it can be rephrased in the following way. The essential conjecture is simply that as one goes up in excitation energy in the baryon spectrum the role of chiral symmetry breaking in determining spectral properties diminishes to the point where the states act to good approximation as though there were no symmetry breaking effects.

A natural language to consider this phenomenon is via correlation functions of currents (interpolating fields) constructed from quark and gluon operators and carrying the quantum numbers of baryons as is done in both the QCD sum rule [2] and in lattice QCD [3]. The correlation functions at high space-like momenta are naturally expressed in terms of an operator product expansion (OPE) [4] which is the basis of QCD sum-rule calculations. Thus, the correlation function at high space-like momenta is dominated by the perturbative contributions; towards smaller momenta it is dominated by condensates (vacuum expectation values of composite operators), whose contributions are governed by inverse powers of momenta relative to the contribution of the three free quark propagators. The correlation function in the deep Euclidean region can be linked to the imaginary parts of the correlators in the time-like region via dispersion relations; one integrates over a spectral function that is the square of the amplitude that the current creates a state of given mass squared. The currents can be constructed to have well defined transformation properties under $SU(2)_L \times SU(2)_R$ transformations. Because of asymptotic freedom it is clear that the correlation functions at asymptotically high momentum can be calculated directly in perturbation theory. However in perturbation theory there is no spontaneous symmetry breaking. The spectrum at asymptotically high mass is connected to only the asymptotically high momentum in correlator. Thus one sees immediately that the chiral $SU(2)_L \times SU(2)_R$ symmetry must be manifest (explicit) in the spectrum at asymptotically high masses (i.e. this spectrum must be insensitive to the effects of chiral symmetry breaking). The spectral density at asymptotically high mass associated with a particular current is identical to the spectral density for a chirally rotated current, i.e. the states form chiral mutliplets. Although the states form chiral multiplets, asymptotically high in the spectrum they cannot be identified with hadrons, because as one increases the mass, the spectrum of resonances becomes increasingly dense and the widths should not decrease. Ultimately the resonances overlap to the point at which it is no longer meaningful to identify part of the spectral density with a given hadronic resonance. Indeed, it is this structure of dense overlapping resonances that allows the hadronic spectrum to approach the perturbative QCD continuum that naively is associated with multi-quark states.

In terms of this language, the conjecture that there is effective chiral restoration in the spectrum of highly excited baryons can be understood as follows: as one goes up in excitation energy the effects of chiral symmetry breaking on the spectrum must diminish as one approaches the perturbative regime. The conjecture, then, is simply that the effect of chiral symmetry breaking cuts off low enough in the spectrum that isolated hadronic resonances are still distinct. This in turn means that chiral symmetry breaking effects become negligible in these correlation functions than at least some other nonperturbative (but chiral invariant) and perturbative effects that are responsible for the overal baryon mass high in the spectrum (in particular the effects responsible for the formation of hadronic resonances which intuitively are related to confinement).

In Sec. II we show how the concept of quark hadron duality allows one to expect the effective chiral symmetry restoration high in the spectrum. Section III is devoted to a classification of the possible parity-chiral multiplets. In Sec. IV we discuss an alternative possibility for parity doubling, namely $U(1)_V \times U(1)_A$ restoration, and show that a $U(1)_V \times U(1)_A$ restoration cannot explain parity doubling unless simultaneously the chiral symmetry $SU(2)_L \times SU(2)_R$ is also restored. In Sec. V we will review the data on highly excited baryonic resonances and show that the pattern of excitations is such that the states can be interpreted as falling into parity-chiral multiplets. In Sec. VI we compare with other approaches and we conclude the present study.

II. WHY SHOULD ONE EXPECT CHIRAL SYMMETRY RESTORATION HIGH IN THE SPECTRUM?

In this section we argue how the concept of quark-hadron duality suggests chiral symmetry restoration high in the spectrum. The phenomenon of quark-hadron duality [5] is well established in many processes, e.g. in $e^+e^- \rightarrow$hadrons, where we have a direct experimental access to creation of the quark-antiquark pair by the electromagnetic current. According to this concept, the spectral density $\rho(s)$ (perhaps appropriately smeared) at the very large s should be dual to the polarization operator calculated at the free quark loop level (up to perturbative corrections). For the process $e^+e^- \rightarrow$hadrons the "asymptotic regime" sets in approximately at $s \sim 2$–3 GeV^2 (within the light flavors sector). The physical picture that is behind such a duality is rather simple. At large s the conversion of the virtual photon into a quark-antiquark pair happens at the very short distances between the quark and antiquark (or during a very small time interval) and so this stage is described by perturbative QCD. Materialization of these quarks and antiquarks into physical hadrons happens at the second stage of the process, where the quark and antiquark are quite far from each other and the nonperturbative QCD phenomena are important here. These nonperturbative phenomena, however, cannot significantly affect the full (inclusive) transition rate (spectral density) which is determined at the first stage of the process.

In the case of baryons, unfortunately, there are no experimentally accessible currents that can create three quarks at some space-time point and connect them to baryons. Nevertheless, one can construct such currents theoretically and these currents are widely used in QCD sum rules or lattice calculations to extract properties of low-lying baryons directly from QCD. The quark-hadron duality applied to the present case would mean that in the asymptotically high part of the baryon spectrum the baryon spectral density should be dual to the one which is calculable in perturbation theory; hence the chiral symmetry should be manifest in the spectral density, because there is no chiral symmetry breaking in perturbation theory.

Consider, as an example, the two-point correlator of the Ioffe current [6] $\eta=\epsilon_{abc}(u^{aT}C\gamma_\mu u^b)\gamma_\mu\gamma_5 d^c$, i.e. one of the currents that couples to isodoublet $J=1/2^+$ and $J=1/2^-$ baryons. This correlator contains chiral even and odd terms

$$\Pi(q)=i\int d^4x e^{iqx}\langle 0|T(\eta(x),\overline{\eta}(0))|0\rangle = \Pi^{even}(q^2)q_\mu\gamma^\mu+\Pi^{odd}(q^2), \qquad (1)$$

which behave differently under discrete chiral transformations of the form $\exp(i\pi\gamma_5\vec{\tau}\cdot\hat{n}/2)$ (with arbitrary $\hat{n}$); while the former is invariant under this transformation; the latter one switches sign.

In the deep space-like domain $q^2<0$, where the language of quarks and gluons is adequate, the OPE up to dimension dim$=4$ operators is [6,7]

$$\Pi^{odd}(q^2)=-\frac{1}{4\pi^2}\langle\overline{q}q\rangle q^2\ln(-q^2)+\cdots, \qquad (2)$$

$$\Pi^{even}(q^2)=\frac{\ln(-q^2)}{32\pi^2}\left(\frac{q^4}{2\pi^2}+\left\langle\frac{\alpha_s}{\pi}G^a_{\mu\nu}G^a_{\mu\nu}\right\rangle\right)+\cdots. \qquad (3)$$

In these equations the first term in the chiral even part of the correlator represents the zeroth order perturbative contribution, i.e. propagation of three free quarks from the point 0, where they are created by the current, to the point x, where they are annihilated by the same current. The second term of Eq. (3), which is the contribution of the gluon condensate, parametrizes soft nonperturbative gluonic effects. Unlike $\langle\overline{q}q\rangle$, the gluon operator $\langle(\alpha_s/\pi)G^a_{\mu\nu}G^a_{\mu\nu}\rangle$ is not a chiral order parameter [8]. Higher order perturbative corrections (containing logarithmic contributions) and the contribution of the higher order chirally even condensates (which are suppressed by powers of $1/q^2$) and that do not break the discrete chiral symmetry are not included in Eq. (3). In contrast, the chiral odd contribution given in Eq. (2) has no purely perturbative part. It consists exclusively of contributions proportional to the various chirally odd condensates. In the expression (2) only the lowest dimension (dim=3) quark condensate is shown explicitly. The contribution of other chirally odd condensates of higher dimension are suppressed by powers of $1/q^2$.

The spectral density, $\rho(s)$, is proportional to the imaginary part of the correlator in the time-like region, $s=q^2>0$. The spectral density parameterizes the amplitude for the current to create a baryon state with mass of $s^{1/2}$ and hence provides direct information about the spectrum. While it is not trivial to calculate $\rho(s)$ directly, it is straightforward to analytically continue the truncated OPE expansion from the deep Euclidean domain to the time-like region. While such a procedure introduces ambiguities, the ambiguities are suppressed as one goes asymptotically high in the spectrum [9]. In the present context, the significant point is that Eqs. (3) and (2) imply that at sufficiently large space-like q^2, $C\Pi^{even}(q^2)\gg\Pi^{odd}(q^2)$, where the dimensional constant C (with dimension MeV) is needed to make a comparison meaningful. Analytically continuing this to the large time-like region implies that for sufficiently large s, $C\rho^{even}(s)\gg\rho^{odd}(s)$. This in turn implies the spectrum is chirally even, i.e. *invariant under the discrete chiral transformation*. However, a stronger constraint can be found for the high-lying spectrum. Up to dimension 4, the chirally even correlator is invariant under more than the discrete chiral rotations used to define "even" and "odd" but under arbitrary chiral rotations. This can be seen explicitly from Eq. (3) which at this order is independent of all chirally active condensates. Thus analytically continuing to large time-like $q^2=s$ one concludes the asympotic spectral function is not only chirally even under the discrete transformation but is chirally invariant under arbitrary chiral transformations. Summarizing, *even if the chiral symmetry is strongly broken in the vacuum (and hence in the low-lying states), one should expect that the effects of chiral symmetry breaking become unimportant for a high-lying spectrum.* This is a simple consequence of the concept of quark-hadron duality.

The Ioffe current that was considered in the example above belongs to the $(1/2,0)\oplus(0,1/2)$ representation of the chiral group. However, one can also construct the currents that transform according to the other representations of this group [10].

III. CLASSIFICATION OF THE PARITY-CHIRAL MULTIPLETS

Regardless of how plausible one views the *a priori* arguments above, it is useful to see whether the conjecture is consistent at the phenomenological level with the spectroscopy of highly excited baryons. In particular, although the principal motivation behind this conjecture was the known parity doublet structure of the excited baryons the conjecture actually implies a stronger constraint on the spectrum.

Effective chiral restoration implies that the physical states fall into chiral multiplets of nearly degenerate states. Let us consider in some detail the structure of those multiplets. The irreducible representations of $SU(2)_L\times SU(2)_R$ may be labeled as (I_L,I_R) where I_L and I_R represent the isospin of the left- and right-handed SU(2) groups. There is an automorphism of $SU(2)_L\times SU(2)_R$, $Q_L^i\leftrightarrow Q_R^i$, where $Q_{L,R}^i$ are the left and right chiral charges and i refers to isospin. This automorphism can be interpreted as the parity operation $L\leftrightarrow R$, under which the vector charge $Q^i=Q_L^i+Q_R^i$ is not affected, but the axial charge $Q_5^i=Q_L^i-Q_R^i$, changes its sign.

QCD with $\theta=0$ respects parity; thus chiral multiplets must be large enough so as to contain states of good parity. This can only happen if the representation transforms into itself under parity—i.e. under parity every state in the representation transforms into another state in the representation. However, in general, the irreducible chiral representations do not trsansform into themselves under parity. A general irreducible chiral representation, (I_a,I_b) transforms under parity into (I_b,I_a), i.e. it cannot be ascribed any definite parity except for those (I,I) that transform into themselves. Thus, if chiral symmetry is effectively restored for a class of states the multiplets must either be chiral multiplets of the form (I,I) or the multiplets must be combined parity-chiral multiplets containing two irreducible chiral representations, i.e. $(I_a,I_b)\oplus(I_b,I_a)$. Moreover, baryons in two flavor QCD cannot fall into (I,I) chiral representations since all states in these representations are of integral isospin while baryons in two flavor QCD are all of half integral isospin. Thus the effective chiral restoration for baryons states implies that they fall into parity-chiral representation of the form $(I_a,I_b)\oplus(I_b,I_a)$ with I_a half integral and I_b integral.

Now let us look at the parity structure of these parity-chiral multiplets. Obviously, they contain parity doublets. For every state of good parity in the multiplet there is another state which has the same total isopin but opposite parity. The reason for this is quite clear. All of these parity-chiral multiplets contain two distinct irreducible chiral representations which transform into each other under parity. A state of good parity can be constructed starting from a state of good isospin in the (I_a,I_b) representation which we denote $|I_{(I_a,I_b)}\rangle$. The states of positive and negative parity are $2^{-1/2}(|I_{(I_a,I_b)}\rangle+P|I_{(I_a,I_b)}\rangle)$ and $2^{-1/2}(|I_{(I_a,I_b)}\rangle-P|I_{(I_a,I_b)}\rangle)$, respectively. Thus, as advertised, effective chiral restoration for this class of states explains the parity doublets. However, in general the parity doublet states of the given isospin are not the only states in the representation that includes states of different isospin. Thus, in general, one expects that the approximate degeneracy of states associated with effective chiral restoration includes more states than the simple parity doublet of the given isospin.

Let us now consider in some detail the phenomenological consequences of effective chiral restoration for states high in the baryon spectrum. As discussed above, such states would have to fall into parity-chiral multiplets with representations of the form $(I_a,I_b)\oplus(I_b,I_a)$ with I_a half integral and I_b integral. States in such representations can have isospins ranging from a maximum of $I=I_a+I_b$ to a minimum of $I=|I_b-I_a|$. Empirically, there are no known baryon resonances which have an isospin greater than 3/2. In the language of the constituent quark model this is equivalent to the statement that there are no known quantum-number exotic baryons. Thus we have a constraint from the data that if chiral symmetry is effectively restored for very highly excited baryons, the only possible representations for the observed baryons have $I_a+I_b \leqslant 3/2$, i.e. the only possible representations are $(1/2,0)\oplus(0,1/2)$, $(1/2,1)\oplus(1,1/2)$ and $(3/2,0)\oplus(0,3/2)$. Since chiral symmetry and parity do not constrain the possible spins of the states these multiplets can correspond to states of any fixed spin. The $(1/2,0)\oplus(0,1/2)$ multiplets contain only isospin 1/2 states and hence correspond to parity doublets of nucleon states (of any fixed spin). Similarly, $(3/2,0)\oplus(0,3/2)$ multiplets contain only isospin 3/2 states and hence correspond to parity doublets of Δ states (of any fixed spin). However, $(1/2,1)\oplus(1,1/2)$ multiplets contain both isospin 1/2 and isospin 3/2 states and hence correspond to multiplets containing both nucleon and Δ states of both parities and any fixed spin.

Summarizing, if $(1/2,0)\oplus(0,1/2)$ and $(3/2,0)\oplus(0,3/2)$ were realized in nature, then the spectra of highly excited nucleons and deltas would consist of parity doublets. However, the energy of the parity doublet with given spin in the nucleon spectrum *a priori* would not coincide with the energy of the doublet with the same spin in the delta spectrum. This is because these doublets would belong to different representations of $SU(2)_L\times SU(2)_R$. On the other hand, if $(1/2,1)\oplus(1,1/2)$ were realized, then the high-lying states in the N and Δ spectra would consist of multiplets that contain one N parity doublet and one Δ parity doublet with the same spin and are degenerate in mass. We stress that this classification is the most general one and does not rely on any model assumption about the structure of baryons.

IV. CAN $U(1)_V\times U(1)_A$ RESTORATION EXPLAIN PARITY DOUBLETS?

Before discussing the data in detail it is useful to consider briefly an alternative explanation for parity doublets in the spectrum, namely effective $U(1)_V\times U(1)_A$ restoration [12]. At first sight this seems to be a more natural explanation of the parity doubling phenomena as it does not seem to require larger multiplets and involves doublets of the given isospin only. One might postulate, for example, that instanton effects responsible for anomalous $U(1)_A$ violations may become unimportant high in the baryon spectrum. However, such a scenario is highly implausible in our view. $U(1)_V\times U(1)_A$ is broken in two ways—explicitly through the axial anomaly (and quark masses) and spontaneously. It is clear that both types breaking are present. Consider, for example QCD with massless quarks in the large N_c limit (or an imaginary world with $N_c=3$ but without axial anomaly). In the large N_c limit all effects of the axial anomaly are absent. However, due to the spontaneous symmetry breaking the pion is massless while its $U(1)_A$ partner, the isovector scalar δ, is not. Indeed the same condensates which break $SU(2)_L\times SU(2)_R$ (such as $\langle \bar{q}q\rangle$) also break $U(1)_V\times U(1)_A$. Thus even if one can argue that the effects of anomalous $U(1)_A$ breaking shut off high in the baryon sector, unless the effects of spontaneous breaking of $SU(2)_L\times SU(2)_R$ also shut off one will not have parity doublets. However, if the effects of the spontaneous breaking of $U(1)_V\times U(1)_A$ do shut off one would expect that the effects of spontaneous $SU(2)_L\times SU(2)_R$ breaking would also shut off as the spontaneous breaking of both types of symmetries involves the same condensates.

V. EXPERIMENTAL DATA

The question of relevance is whether the observed baryon high-lying resonances fall into these representations. This is not trivial to determine for a number of reasons. The first is that even if the conjecture is correct the effective chiral restoration is only approximate due to both quark mass effects and residual effects of spontaneous symmetry breaking. Moreover, we have no tools to estimate in an *a priori* fashion the expected size of these symmetry-breaking effects high in the baryon spectrum. Thus some judgment is need to assert that two levels are "nearly degenerate." A second complication stems from the fact that this high in the spectrum there are many levels close together and one cannot rule out the possibility that two states are near each other in energy by accident. Moreover, the experimental data [13] is neither perfect nor complete in this region and the extraction of resonance masses from the data introduces additional uncertainties.

Keeping all these in mind, we note, however, that the known empirical spectra of the high-lying N and Δ baryons suggest remarkable regularity. Below we show all the known N and Δ resonances in the region 2 GeV and higher and include not only the well established baryons ("****" and "***" states according to the Particle Data Group (PDG) classification [13]), but also "**" states that are defined by PDG as states where "evidence of existence is only fair." In some cases we will fill in the vacancies in the classification below by the "*" states, that are defined as "evidence of existence is poor" and mark these states by (*): for $J=\frac{1}{2}$:

$$N^+(2100)(*),N^-(2090)(*),\Delta^+(1910),\Delta^-(1900);$$

for $J=\frac{3}{2}$:

$$N^+(1900),\ \ N^-(2080),\ \ \Delta^+(1920),\ \ \Delta^-(1940)(*);$$

for $J=\frac{5}{2}$:

$$N^+(2000),\ \ N^-(2200),\ \ \Delta^+(1905),\ \ \Delta^-(1930);$$

for $J=\frac{7}{2}$:

$$N^+(1990),\ \ N^-(2190),\ \ \Delta^+(1950),\ \ \Delta^-(2200)(*);$$

for $J=\frac{9}{2}$:

$$N^+(2220),\ \ N^-(2250),\ \ \Delta^+(2300),\ \ \Delta^-(2400);$$

for $J=\frac{11}{2}$:

$$?,\ \ N^-(2600),\ \ \Delta^+(2420),\ \ ?;$$

for $J=\frac{13}{2}$:

$$N^+(2700),\ \ ?,\ \ ?,\ \ \Delta^-(2750);$$

for $J=\frac{15}{2}$:

$$?,\ \ ?,\ \ \Delta^{+}(2950),\ \ ?.$$

The data above suggest that the parity doublets in N and Δ spectra are approximately degenerate; the typical splitting in the multiplets are ~ 200 MeV or less, which is within the decay width of those states. Of course, as noted above,"nearly degenerate" is not a truly well-defined idea. In judging how close to degenerate these states really are one should keep in mind that the extracted resonance masses have uncertainties which are typically of the order of 100 MeV.

Though one cannot rule out the possibility that (i) the approximate mass degeneracy between the N and Δ doublets is accidental [then it would mean that baryons are organized according to $(1/2,0)\oplus(0,1/2)$ for N and $(3/2,0)\oplus(0,3/2)$ for Δ parity-chiral doublets] we believe that this fact supports an idea (ii) that the highly excited states fall into approximately degenerate multiplets $(1/2,1)\oplus(1,1/2)$.

While a discovery of states that are marked by (?) would support the idea of effective chiral symmetry restoration, a definitive discovery of states that are beyond the systematics of parity doubling, would certainly be strong evidence against it. The nucleon states listed above exhaust all states ("****," "***," "**," "*") in this part of the spectrum included by the PDG. However, there are some additional candidates (not established states) in the Δ spectrum. In the $J=5/2$ channel there are two other candidate states $\Delta^{+}(2000)(**)$ and $\Delta^{-}(2350)(*)$; there is another candidate for the $J=7/2$ positive parity state—$\Delta^{+}(2390)(*)$ as well as for $J=1/2$ negative parity state $\Delta^{-}(2150)(*)$. Certainly a better exploration of the highly lying baryons is needed.

VI. DISCUSSION

If our conjecture is correct, and assuming that the correlator of three quarks does couple to these states (*a priori* one cannot rule out the possibility that these states are not strongly coupled to the three quark correlator, but do couple to the correlator that contains 5 quark fields, etc.) it would imply that these highly excited baryons behave as though they were made out of two left and one right quark fields (and vice versa).

The conjecture of "effective chiral restoration" with the states in the $(1/2,1)\oplus(1,1/2)$ representation seems to be in qualitative agreement with the spectroscopic data. However, it is essential to consider how the conjecture can be tested, i.e. to determine what possible types of evidence can be found which would support the conjecture or rule it out. The right-left structure of these states might be in principle studied in weak processes, but as a practical matter this is not possible since the lifetime of these states is much below the typical time of weak interactions. In the future, if one is able to describe these states directly from QCD the conjecture could be checked directly; specifically, one can test whether the states in question only couple strongly to currents with $(1/2,1)\oplus(1,1/2)$ quantum numbers.

Finally we wish to discuss the relation of the present work with a scheme recently introduced by Jido, Hatsuda and Kunihiro (JHK) which, in the context of the generalized σ model, organizes *low-lying* baryon fields into the representations $(1/2,1)\oplus(1,1/2)$ [11]. In fact, the two schemes are quite different. The present work is based on the notion that high-lying baryons physical *states* behave as if they approximately form $(1/2,1)\oplus(1,1/2)$ multiplets; our arguments are based on the quark-hadron duality. In contrast, the JHK scheme is based on low-lying baryon *fields* falling into such multpilets. The distinction between the symmetry properties of fields and of states is critical. Of course, if the vacuum had not spontaneously broken chiral symmetry (or had the symmetry breaking effects been very weak), then by acting with these fields on the vacuum one would obtain multiplets of (nearly) degenerate states in the $(1/2,1)\oplus(1,1/2)$ representation. However, the vacuum *does* break the symmetry strongly and the physical states in JHK scheme are *not* eigenstates of chirality and do not correspond to degenerate chiral multiplets as the high-lying states do in the scheme presented here.

It is worth noting in passing that the JHK scheme also implicitly assumes that these fields when acting on the (chirally broken) vacuum produce single narrow resonance states. This assumption implies a one-to-one correspondence between the fields (which form parity-chiral multiplets) and the low-lying physical states. While one may entertain this assumption as a hypothesis for the way QCD dynamics plays out, it is not obvious *a priori* whether such a hypothesis can be justified. It could be justified only if there were a *continuous* smooth "transition" from the Wigner mode (where the whole spectrum would consist of chiral multiplets) to Nambu-Goldstone one or if the chiral symmetry breaking effects in the vacuum represented only a small perturbation. Indeed, the phenomenological data does *not* allow us to classify all the existing low-lying baryons into chiral multiplets and as a consequence the well established states $N(1700)$, $N(1710)$, $\Delta(1600)$, and $\Delta(1920)$ do not fall into JHK multiplets with other known resonances. On the contrary, as argued in the present paper, the chiral symmetry breaking effects do represent only a small perturbation at large s and hence one can expect the physical spectrum there to consist only of parity-chiral multiplets. Thus the high-lying states can fall into multiplets as hypothesized here without the low-lying baryon fields being organized into chiral multiplets as in the JHK scheme.

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[1] L.Ya. Glozman, Phys. Lett. B **475**, 329 (2000).
[2] P. Colangelo and A. Khodjamirian, in *At the Frontier of Particle Physics/Handbook of QCD*, edited by M. Shifman (World Scientific, Singapore, 2001).
[3] I. Montvy and G. Münster, *Quantum Fields on the Lattice* (Cambridge University Press, Cambridge, England, 1994).
[4] K.G. Wilson, Phys. Rev. **179**, 1499 (1969).
[5] E.C. Poggio, H.R. Quinn, and S. Weinberg, Phys. Rev. D **13**, 1958 (1976).
[6] B.L. Ioffe, Nucl. Phys. **B188**, 317 (1981); **B191**, 591(E) (1981).
[7] L.J. Reinders, H. Rubinstein, and S. Yazaki, Phys. Rep. **127**, 1 (1985).
[8] M. Shifman, Prog. Theor. Phys. Suppl. **131**, 1 (1998).
[9] M. Shifman, in *At the Frontier of Particle Physics/ Handbook of QCD*, edited by M. Shifman (World Scientific, Singapore, 2001).
[10] T.D. Cohen and X. Ji, Phys. Rev. D **55**, 6870 (1997).
[11] D. Jido, T. Hatsuda, and T. Kunihiro, Phys. Rev. Lett. **84**, 3252 (2000).
[12] S. Capstick *et al.*, hep-ph/0012238.
[13] Particle Data Group, D. Groom *et al.*, Eur. Phys. J. C **15**, 1 (2000).