Explanation why the Θ^+ is seen in some experiments and not in others

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To understand the whole set of positive and null data on the $\Theta^+(1530)$-production, we suggest the hypothesis that multiquark hadrons are mainly generated from many-quark states, which emerge either as short-term hadron fluctuations, or as hadron remnants in hard processes. This approach allows us to describe both nonobservation of the Θ^+ in current null experiments and peculiar features of its production in positive experiments. Further, we are able to propose new experiments that might be decisive for the problem of the Θ^+ existence. Studies of properties and distributions of the Θ^+ in such experiments can give important information on the structure of both conventional and multiquark hadrons. It would provide better insight into how QCD works.

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I. INTRODUCTION

Invented more than 40 years ago [1–3], quarks were initially introduced rather formally, to account for a very limited variety of hadronic flavor multiplets known at that time. Their simplest application was to present every baryon as a three-quark system and every meson as a quark-antiquark system. Then, in respect to the flavor symmetry group $SU(3)_F$, the mesons could exist only as singlets and/or octets, while the baryons could reveal both the same kinds of multiplets and, in addition, decuplets.

Such a simple conventional picture was in good correspondence with experiment. It could be quite successful, if the quarks were nothing more than mathematical objects allowing to visualize symmetry classification of hadrons (such treatment would not contradict to Gell-Mann's paper [2]). However, if quarks (or "aces," in Zweig's terminology [3]) are physical objects, the picture of hadrons with a fixed number of constituents could be self-consistent only in a nonrelativistic theory. In a relativistic case, production and annihilation of virtual quark-antiquark pairs prevent the total number of quarks and antiquarks from being fixed. That is why the first hints, that the quarks might be something more than just mathematical objects, revived the question whether one would be able to observe hadrons with nonconventional quark content, entering some other kinds of flavor multiplets and, in particular, having exotic quantum numbers, impossible in the conventional picture.

One of the simplest clear examples of non-3-quark baryons would be a baryon with positive strangeness, say, a resonance in the KN system with $S = +1$ (by definition, the strange quark s has $S = -1$, and a 3-quark system cannot have $S = +1$). Experimental searches for such exotic states in the KN-spectra started rather early [4–6]. However, all suggested evidences stayed unconvincing, and later the Particle Data Group stopped discussions on experimental spectroscopy of exotics [7].

The first theoretical attempt to describe internal dynamical structure for specific multiquark hadrons was made in the framework of the "MIT bag" [8–10]. The calculations supported existence of exotic states, but prescribed them to be very broad, with widths of some hundreds MeV. This result seems quite understandable, since an exotic multiquark system in the MIT bag looks to be readily prepared for separation into subsystems with conventional quark contents: a tetraquark meson $qq\bar{q}\,\bar{q}$ may be considered as a system of two quark-antiquark pairs, while the pentaquark baryon $qqqq\bar{q}$ may be considered as $(3q + q\bar{q})$. According to the MIT-bag approach, it is just the enormously huge width that could explain why exotic resonances have not been seen in experiment: they exist, but are too broad to reveal clear-cut bumps. Totally unnoticed for a long time has stayed an alternative possibility: the fact that hadrons have an internal structure may suggest some hadrons to have a very complicated structure which would suppress their couplings (and, therefore, production cross sections and decay widths) to conventional hadrons [11]. It could be similar to "structural" suppression of some radiative transitions, which is well known in atomic physics. Such a possibility has been recently demonstrated by detailed calculations for the system of $(4q)\bar{q}$ [12].

It is interesting that the standard partial-wave analysis of the elastic KN-scattering [13] (the latest and most complete one published up to now) has later presented four exotic baryon states (resonances), two isoscalar and two isovector, all having, indeed, large widths 200–500 MeV. However, even before the publication [13], any correspondence between the MIT bag and experiment had begun to look generally dubious.

A new impetus for studies of exotics has emerged [14] from the chiral quark soliton approach (χQSA; for recent reviews, see Refs. [15,16]). It allowed one to give a rather detailed theoretical prediction of the exotic antidecuplet of baryons (including the Θ^+ with $S = +1$) and strongly stimulated new experimental searches for exotics. These efforts gave, at last, some positive evidences, as summarized in the Review of Particle Properties issue of 2004 [17].

Nevertheless, the current experimental status of the exotic baryon $\Theta^+(1530)$ is rather uncertain (see the more recent experimental review [18] and the latest edition of the Review of Particle Properties [19]). Some collaborations give positive evidences for its observation, some others do not see it, thus casting doubts on existence of the Θ^+ and on correctness of its positive evidences. Especially impressive are the recent high-statistics null results of the CLAS Collaboration for Θ^+-photoproduction into several final states [20–23]. Yet, new (“after-CLAS”) dedicated analyses have again provided both confirming [24–28] and null [29–33] publications. Moreover, a new suggested way [34] for data analysis may reveal the presence of the Θ^+ even in the published CLAS results, through its interference with a known resonance.

At present, an important fact is that there are no data sets, from independent groups, with exactly overlapping observational conditions (initial and/or final states, kinematical regions). Therefore, when comparing today different current data on the Θ^+, one needs some theoretical models/assumptions for the unknown production mechanisms. Thus, one cannot yet reject experimental existence of the $\Theta^+(1530)$ as a particular exotic pentaquark baryon. On the other side, we emphasize also that, up to now, there has not been suggested, in the framework of quantum chromodynamics (QCD) or in some other terms, any theoretical reason to forbid multiquark hadrons.

In such an uncertain situation, Karliner and Lipkin [35,36] raised the question shown in the title here, why the Θ^+ is seen in some experiments and not in others. As an answer, they suggested an important role of the baryon resonance with hidden strangeness $N(2400)$ (see also Ref. [37]). However, this particular resonance production seems to be insufficient today to explain many of the positive evidences.

An opposite viewpoint is that all positive results might arise as statistical fluctuations and do not reveal a true physical effect (see, e.g., Ref. [38]). However, it would be strange to have the same fluctuation in data of more than ten independent groups studying very different processes. Moreover, in such a case we should live with the open question of what prevents exotic hadrons from being existent.

Therefore, we assume in the present paper that the Θ^+, as a representative of exotic hadrons, does exist and has properties corresponding to the published positive evidences: rather low mass and unexpectedly narrow width. Then we are going to reconsider possible dynamical picture for multiquark hadrons. Though our approach is still qualitative, not quantitative yet, it seems to reconcile different data and explain some regularities in (non)observation of the Θ^+. It allows, further, to suggest new experiments for confirmation and more detailed studies of the Θ^+-production and its properties.

II. EXPERIMENTAL Θ^+-PRODUCTION

Up to now, positive evidences have been published for three exotic baryons: $\Theta^+(1530)$, $\Theta_c^0(3100)$, and $\Xi_{3/2}^{--}(1860)$ [or $\Phi^{--}(1860)$] [19]. Each of the two latter states was seen by one group only; they have not been found in other dedicated experiments. That is why we will not discuss them here. More crucial in the present situation appears the existence or nonexistence of the Θ^+. The corresponding information (positive or negative) is much more copious than for any other exotic hadron candidate.

When considering the Θ^+ to be a real object, we encounter a problem, whether all existing positive and null data may be mutually consistent. This seems doubtful under the assumption of familiar hadroproduction mechanisms. However, a very small width of the Θ^+ provides a hint of an unfamiliar mechanism for the Θ^+-decay. If so, the production mechanism, most probably, should be unusual as well.

Up to now, only some of the data, both published and preliminary, seem to touch not only a problem of the Θ^+-existence, but also a possible mechanism of its production. It is natural, therefore, to pay special attention just to such data. We will discuss the positive and negative experimental data separately.

A. Positive data

(a) ZEUS data.—Let us begin with results from the ZEUS detector at HERA on the Θ^+-production in the deep-inelastic scattering (DIS). They are most advanced in respect to the production mechanism.

As is known, DIS is a typical hard process. At the parton level, it essentially corresponds to the virtual photon knocking out a parton from the initial hadron (proton, in the case of HERA). Respectively, the final hadrons in DIS may be separated into two parts: the current fragmentation region, with final hadrons mainly produced in hadronization of the knocked-out parton, and the target fragmentation region, where final hadrons come mainly from hadronization of the target remnant. Note that the latter case has never been described from first principles of QCD (see, however, some attempts [39]).

The ZEUS Collaboration has found both the $\Theta^+(1530)$ and its antiparticle [40].[1] They are seen in the kinematical region, which was believed to be related with fragmentation of the knocked-out parton(s) [43,44]. The proton remnant has been usually considered to escape nearly

[1]Note that the H1 Collaboration, also at HERA, does not see the $\Theta^+(1530)$ [41]. However, both ZEUS and H1 Collaborations agree that their data do not contradict each other. Recent analysis with comparison of the two data sets is given in Ref. [42].

unnoticed by the ZEUS detector. In any case, the remnant contribution in the region used was assumed to be negligible. Such expectations have been confirmed by measurements of fragmentation functions for various identified hadrons. In particular, the ZEUS Collaboration measured fragmentation fractions for different charmed hadrons in this kinematical region [45]. They coincide quite well with those measured in e^+e^- annihilation. Such coincidence was predicted for DIS in the current fragmentation region [fragmentation of the knocked-out (anti)quark is expected to be nearly the same as fragmentation of the (anti)quark produced in e^+e^- annihilation] [39].

Special attention was given to production properties of the baryons $\Lambda(1520)$ and $\Lambda_c^+(2285)$, since they could be kinematically similar to production of the $\Theta^+(1530)$. It appears [46] that the $\Lambda(1520)$ and $\Lambda_c^+(2285)$ are produced as expected: $\Lambda(1520)$ through fragmentation of the knocked-out quark, while $\Lambda_c^+(2285)$ through fragmentation of the $c\bar{c}$-pair, generated by the γ^*-gluon fusion.

However, $\Theta^+(1530)$ in the same kinematical region clearly demonstrates distributions which are characteristic for hadronization of the target-proton remnant (in particular, it is mainly produced in the forward hemisphere, i.e., at positive pseudorapidity η) [46]. Thus, even in the region that seems kinematically related to the current fragmentation, contribution of the knocked-out parton(s) to the $\Theta^+(1530)$-production appears to be small, if present at all. This is a very essential difference between processes of producing the exotic $\Theta^+(1530)$-baryon or various conventional 3-quark baryons, such as $\Lambda(1520)$ and $\Lambda_c^+(2285)$.

The proton remnant in DIS is always a mixture of various many-quark configurations, contrary to a few-quark system of the knocked-out parton(s). Thus, the above ZEUS data allow us to suggest the hypothesis that the Θ^+-production comes mainly from hadronization of many-quark (or, more generally, many-parton) systems.

With such hypothesis, we should expect that the Θ^+-production in DIS may change with Q^2, due to the changing role of different many-parton configurations. Experimentally, the absolute Θ^+-yield in the ZEUS data decreases with increasing $Q^2_{\rm min}$ at $Q^2 > 20$ GeV^2 [44]. However, it is mainly due to the factor $1/Q^4$ coming from the photon propagator squared. This universal factor has no relation to remnant configurations and can be eliminated, if one considers the relative yield of the Θ^+ in respect to conventional hadrons. The ZEUS Collaboration investigated the ratio $\Theta^+(1530)/\Lambda(1116)$ in the same kinematical region. Instead of decrease, this ratio shows a slow increase; though, with current large uncertainties, it may be considered also as a constant, about 4% [44].

Such a situation reminds one of the case of nucleon structure functions, which initially seemed to be Q^2-independent (Bjorken scaling). But later, both theoretical considerations and more precise measurements have revealed scaling violations in the structure functions, with slow (logarithmical) dependence on Q^2. Since the underlying physics, the enhanced role of many-parton configurations at higher Q^2, is the same in these two cases, we expect that the ratio $\Theta^+(1530)/\Lambda(1116)$ should also logarithmically change (increase?) at high Q^2. Evidently, it is a prediction for future experiments, which can, thus, check our hypothesis.

Meanwhile, we would like to discuss one more feature of the ZEUS data. The Θ^+-peak is not seen in the pK_S spectrum at $Q^2 > 1$ GeV^2 [40]. In the HERA kinematics, one has $W^2 < 10^5$ GeV^2, where W is the $(\gamma^* p)$ c.m.-energy, and the above restriction for Q^2 may be rewritten for the Bjorken variable $x = Q^2/(W^2 + Q^2)$ as $x > 10^{-5}$. A very interesting point is that the ZEUS data do demonstrate the Θ^+-peak even at $Q^2 > 1$ GeV^2, if one applies the additional restriction $W < 125$ GeV [40], i.e.,

$$x > 6.4 \times 10^{-5}. \tag{1}$$

It is well known, on the other side, that nucleon structure functions increase at very small x. Therefore, the larger contributions to the DIS inclusive hadroproduction (in particular, to the pK_S continuum spectrum) at $Q^2 > 1$ GeV^2 should come from the lower region,

$$10^{-5} < x < 6.4 \times 10^{-5}, \tag{2}$$

which violates condition (1). Thus, the ZEUS data [40] imply that the Θ^+-production in DIS depends on x and in the region (2) should not have such enhancement (if any), which appears at small x for the usual DIS production of the background nonresonant pK_S system. Note that, kinematically, the region (2) cannot be reached at HERA in other Q^2-regions investigated by ZEUS (more exactly, at $Q^2 > 6$ GeV^2). This might explain why observability of the Θ^+-peak in the ZEUS data does not need any additional restrictions for W (or x) at higher Q^2.

The two quantities, Q^2 and x, are, generally, independent variables, and a definite value of x may (and, most probably, does) select some states among various many-parton configurations with the "life time" $\sim 1/\sqrt{Q^2}$, corresponding to the used value of Q^2. If the Θ^+ is not produced indeed at too small x, it could mean that typical states of the remnant with presence of a quark having such x may have properties (e.g., quark energy distributions) that suppress the Θ^+-formation. Future experiments could study both Q^2 and x dependencies of the Θ^+-production in more detail, to extract interesting information on structure of both the proton remnant and the Θ^+ itself. The related problems seem to be worthy of more detailed theoretical discussion elsewhere.

(b) Some other positive data.—Hadron remnants emerge in all hard processes having hadron(s) in the initial state (DIS, Drell-Yan pair production, production of high-p_T hadrons, and so on). But many-parton configurations may contribute also to nonhard (soft) processes, e.g.,

through higher Fock components of the initial hadrons. In the framework of our hypothesis, they also can generate the Θ^+.

The corresponding manifestations of the Θ^+-production mechanism are possibly seen in preliminary data of the SVD Collaboration. Its higher-statistics analysis [25,26] has confirmed the earlier evidence for production of the $\Theta^+(1530)$ in nucleon-nucleon collisions [47]. Moreover, preliminary data of this collaboration provide distributions of the Θ^+ in the Feynman variable x_F and in p_T.

The x_F-distribution for the $\Theta^+(1530)$ appears to be very soft: no $\Theta^+(1530)$ is seen at $|x_F| > 0.3$ [26,48], while the observed yield of $\Lambda(1520)$ is much harder: it has maximum at $|x_F| = 0.4$ [48]. Distribution of the Θ^+ over p_T is also soft (no Θ^+ at $p_T > 1.5$ GeV) [48]. The two distributions together imply that the total c.m.-momentum of the produced Θ^+ is not higher than 1.5 GeV, essentially smaller than kinematically available [and than that for $\Lambda(1520)$]. Such properties look quite natural in the framework of our hypothesis. If the pentaquark $\Theta^+(1530)$ is indeed produced from many-parton configurations, then we expect that accompanying hadron multiplicity for the pentaquark $\Theta^+(1530)$ is higher than, say, for the conventional hyperon $\Lambda(1520)$, which is mainly produced through fewer-parton configurations. This makes the c.m.-energy, available for the $\Theta^+(1530)$, smaller than that for the $\Lambda(1520)$.

Similar evidence may come also from preliminary data of the HERMES Collaboration [49]. When the standard kinematic constraints, used for the Θ^+-observation, are appended by the requirement of an additional detected pion, the signal/background ratio essentially improves. It reaches 2:1, instead of 1:3 in the published HERMES data [50]. Up to now, such a quite unexpected result had no explanation, except trivial assumptions of a possible artifact or an experimental error. Our hypothesis allows one to understand it in a reasonable way. The condition of an additional pion in the detector enhances the role of events with higher multiplicity, where, as we argue, the pentaquarks should be present with higher rate, in respect to conventional hadrons, than in average events.

B. Null data

(a) Low-energy measurements.—Two collaborations have published impressive null results on the $\Theta^+(1530)$ at low (or relatively low) initial energies.

One of them, the Belle Collaboration, used low-energy kaons, produced in e^+e^--annihilation, for secondary scattering inside the detector [51]. Physically, this experiment is similar to that of DIANA [27,52], so they may be directly compared. In both cases, one studies the charge exchange reaction $K^+n \to pK_S$ inside a nucleus and looks for the Θ^+ as an intermediate resonance. Experimental results on this charge exchange process can be directly interpreted in terms of the Θ^+-width. The Belle data do not show any Θ^+-signal and provide the restriction [51]

$$\Gamma_{\Theta^+} < 0.64 \text{ MeV}, \tag{3}$$

which may cast doubt on the value

$$\Gamma_{\Theta^+} = (0.9 \pm 0.3) \text{ MeV}, \tag{4}$$

extracted by Cahn and Trilling [53] from earlier DIANA analysis [52]. However, that publication was incomplete, and some additional assumptions on the background contributions were necessary to extract the value (4). A more detailed analysis of the higher-statistics DIANA data [27] allows one to find the width with much less assumptions. Its new value [27]

$$\Gamma_{\Theta^+} = (0.36 \pm 0.11) \text{ MeV} \tag{5}$$

looks extremely low,[2] but does not contradict any other experimental result on Γ_{Θ^+}. In particular, with this new value, the current Belle data cannot exclude existence of the Θ^+.

Note that the value (5) is not yet quite understood theoretically. Expectation of a narrow Γ_{Θ^+} appeared when the χQSA provided evidence for calculational suppressions in some coupling constants of exotic hadrons [14,16,54]. Moreover, traditional methods of χQSA, related to decomposition in $1/N_c$, allow one to find upper bounds for those coupling constants. As a result, such methods predict $\Gamma_{\Theta^+} \lesssim 15$ MeV [14], which is very low in comparison with familiar widths of baryonic resonances ($\sim$ 50–100 MeV). The "model-independent approach" to the chiral quark soliton, using phenomenology of the proton spin content and hyperon semileptonic decays, has recently shown [55] that the χQSA may be consistent with $\Gamma_{\Theta^+} < 1$ MeV and even with the value (5). However, this approach cannot yet fix a particular theoretical value for the width. Moreover, it has not explained a physical reason for the suppression of Γ_{Θ^+}.

Progress in understanding the Θ^+-width seems to be related with the Fock column picture of hadrons [56]. Starting from the soliton of χQSA, the baryons were described at the light cone as a set of quarks (3 quarks appended by additional $q\bar{q}$ pairs) in the self-consistent mean chiral field. This way, with various corrections, has lowered the theoretical value down to $\Gamma_{\Theta^+} \approx 0.43$ MeV [57–59], just comparable with the experimental value (5). If this way is correct, it opens possibility for physical explanation of such a tiny width. The reason is participation of hadronic higher Fock components in the process of the Θ^+-decay. Evidently, it is similar to our present hypothesis, which suggests participation of hadronic higher Fock components in the process of the Θ^+-production.

The other set of null data is given by the CLAS measurements of photoproduction off proton and neutron (inside the deutron). Despite impressive experimental

[2] Of course, it is much smaller than the experimental resolution. The method of extraction of such small width is described in Ref. [53].

statistics, treatment of several final states has not revealed any reliable Θ^+-signal [20–23]. These results could pretend to disprove positive evidences of LEPS. However, the kinematical region of the CLAS detector cannot completely overlap that of the other one (the problem is mainly related with the forward direction), so a more detailed comparison is necessary for definite conclusions.

Some current theoretical estimations [60,61] predict even lower cross sections for the Θ^+-photoproduction than the experimental upper limits of CLAS. Of course, it is not clear at present, whether such expectations may agree with the latest positive observations of LEPS [24]. However, today's predictions have essential theoretical uncertainties, which touch, first of all, form factors in exchange diagrams. The published calculations apply form factors with properties familiar for conventional hadrons. However, the form factors may be different, if the transition, say $N \to \Theta^+$, goes mainly in 5-quark (or higher) configuration(s). According to ideas of Feynman [62], the more constituents a system has, the faster its form factor should change (decrease).[3] Then, according to our hypothesis, photoproduction of the pentaquark Θ^+ on the nucleon should go as on a 5-quark system, with a form factor having steeper t-dependence than in photoproduction of conventional hadrons. This might produce the sharp angular distribution which would make mutually consistent the observation of the Θ^+, e.g., in the forward-looking detector LEPS and its nonobservation in the less-forward-looking detector CLAS. In addition, if the CLAS data really contain a small Θ^+-signal, consistent with the published bounds, this signal may be enhanced to the observable level due to interference effects [34]. Thus, the published CLAS data cannot yet pretend to reject existence of the Θ^+.

This is even more true for the COSY-TOF data. The new measurements [32] do not confirm earlier evidence of the same collaboration for the Θ^+-baryon in the reaction $pp \to pK^0\Sigma^+$ [63]. Instead, they set a strict limit for the Θ^+-production. However, their new upper boundary for the cross section is still higher than the theoretical estimation [64] obtained before both new and older analyses.

(b) High-energy measurements.—Null results have been published also for several types of processes considered to be high-energy ones. We begin with $e^+e^- \to$ hadrons (and/or $\gamma\gamma \to$ hadrons). Such processes at high energies go mainly through the prompt production of one quark-antiquark pair, which then hadronizes. This favorably leads to purely mesonic final states (the additional $q\bar{q}$-pair may be produced in a soft manner). Events with baryon-antibaryon pairs need 3 prompt quark-antiquark pairs (i.e., two more pairs) and provide only a small part (phenomenologically less than, say, $1/10$) of all high-energy events. Production of pentaquark baryon(s) needs even more, 5 prompt quark-antiquark pairs (two additional pairs in comparison with conventional baryon events). Thus, one may expect that the rate of events with pentaquark(s) in high-energy e^+e^- annihilation is less than $1/10$ of events with conventional baryons. Current experimental data have not reached sufficient precision to observe them at such a level.

Similar (and even stronger) conclusions are also true for charmonium decays, where modes with baryon-antibaryon pairs have the rate of order $1/100$ in respect to purely meson modes. This implies that pentaquarks in charmonium decays may be expected to have a rate not more than $1/100$ in regard to conventional baryons. Detailed analysis [37] shows that the corresponding experimental data have strongly insufficient precision.

In hadron-hadron collisions, there is the negative search for the Θ^+ by the SPHINX Collaboration [65]. It is usually claimed to reject the SVD positive result [25,26,48] (the two collaborations collected their data at the same Serpukhov proton beam of 70 GeV). However, the SPHINX detector is sensitive mainly to the area of diffraction dissociation (excitation) of the initial proton. At the Serpukhov energy, this process can be well described by an effective pomeron interacting with constituent quarks, without changing the number of constituents. Therefore, our hypothesis implies strong suppression of multiquark baryons in the SPHINX experiment. The suppression may be weaker in the SVD case, where the contribution of many-quark fluctuations could provide a more noticeable effect than in a special case of diffraction dissociation. The SVD and SPHINX measurements have been compared also from a different, "instrumental" viewpoint by the authors of Ref. [42]. They also conclude that the SVD data are more favorable to search for the narrow baryon $\Theta^+(1530)$.

Large sets of high-energy data for the Θ^+-search in hadron-hadron collisions has been obtained at hadronic colliders. Their detectors usually tag events with high values of the transverse energy. Such events are mainly initiated by partons knocked out from initial hadrons, which then hadronize essentially as few-parton systems. Multiquark hadrons should be very rare in their hadronization products. For the same events, our hypothesis suggests to expect a higher rate of exotic hadron production in remnants of the initial hadrons. However, these remnants are practically lost for the FNAL detectors CDF and/or D0. The same is true for the main RHIC detectors, at least, in symmetric collisions $p + p$, $Cu + Cu$, and $Au + Au$. Up to now, dedicated investigation of the hadron remnants has not been planned for those collider detectors in any approved experiments.

Thus, the current high-energy data, which do not see the Θ^+, cannot be decisive for the pentaquark problem, even

[3] The underlying physics is rather transparent: to change the motion of a whole system of many constituents, one should realize many interactions between all those constituents, so to drag each of them.

despite their greater statistics. In the framework of our hypothesis, the reason is that they investigate kinematical regions where multiquark hadrons are produced with a very low rate.

C. Suggestions for further experiments

Though we do not review all existing data, the above examples show that our hypothesis about exotics production mechanism allows one to reconcile current positive and null experiments on the Θ^+-baryon. Even more, it suggests new approaches for studying multiquark hadrons. The corresponding experiments should be oriented to hadrons produced from many-quark systems. As we explained, a clear example of such systems is provided by hadron remnants in hard processes with initial hadrons. At current symmetric configurations of the colliding beams, the remnants escape into tubes of the storage rings. Thus, to investigate them, one would need to essentially modify the existing detectors, to register forward-going hadrons with very high rapidity.

Directions of necessary modification may be demonstrated by the BRAHMS forward spectrometer. It has recently presented the first measurements of high-rapidity production of pions, kaons, protons, and their antiparticles in pp-collisions at RHIC ($y_{\mathrm{had}} \approx 3$, while $y_{\mathrm{beam}} = 5.4$ at $\sqrt{s} = 200$ GeV) [66]. The data for pions and kaons agree with calculations up to next-to-leading-order in the perturbative QCD, but (anti)protons in that region show yet unexplained deviations from expected distributions (see Ref. [66] for more detailed comparison of data vs calculations). Baryon spectroscopy in this region may also reveal unexpected features.

Another approach could be applied, if one used, say, at the FNAL collider, an asymmetric configuration with p and $\bar{p}$ beams of unequal energies. Then, the Lorentz boost would increase the angular dimension for the remnant of the less-energetic hadron, so it could be seen even in the existing detectors, without their modifications. Such a way would allow one to investigate kinematical regions in high-energy hadronic collisions, which have not been seen up to now and which could provide, as we expect, a higher rate of exotics production, than in the published collider experiments.

Note that there exist asymmetric colliders. For instance, the B-factories at SLAC and KEK are the asymmetric e^+e^--colliders. But they study the process $e^+e^- \to$ hadrons, where, as we explained, exotic baryon production should be an exotic process indeed. The HERA facility at DESY is also just an asymmetric collider. However, its asymmetry (the proton momentum much higher than the electron one) is such that the detectors ZEUS and H1 favor investigations of the current fragmentation region, while the target fragmentation region, directly related to the proton remnant, is strongly shrunk. We expect that the HERA run with the less-energetic proton beam could allow the ZEUS detector (and may be H1 as well) to study in more detail the proton remnant contributions. A very interesting and perspective direction of studies could be investigation of x- and Q^2-dependencies of the Θ^+-production in DIS. In particular, we expect that, with Q^2 growing, the ratio of exotic/conventional hadron yields should logarithmically increase, in analogy with a logarithmic increase of the small-x hadronic structure functions.

Many-quark systems may emerge also in soft processes, due to short-term fluctuations of initial hadron(s). However, their relative contribution is usually rather small and, thus, should provide a rather small cross section for the exotics production, as compared to conventional hadron production.[4] To increase an exotics signal/background ratio, one needs to apply some selections enhancing the role of many-parton fluctuations. A possible way could be to study events with high (total or charged) hadron multiplicity. Of course, such events have larger combinatorial background. But we expect that the relative yield of the exotic Θ^+-baryon vs a conventional baryon, say, $\Lambda(1520)$, should be enhanced for such events in comparison to the total set of events. Properties of the Θ^+-production, as observed by the SVD Collaboration [25,26,47,48], show that also useful for the exotics observation might be restriction to relatively low energy of the (KN)-pair (as we have explained, this is also related to the enlarged multiplicity).

The two latter points may be essential in evaluating null-result experiments for exotics searches. Some of those experiments, because of "technical" reasons, apply restrictions on particle energies and/or on multiplicity of selected events. The above discussion demonstrates that these restrictions can suppress (or enhance) the relative exotics production. Such possibilities should be taken into account in planning future experiments.

III. CONCLUSIONS AND DISCUSSIONS

Let us summarize the above considerations. On the base of some positive experimental data, we assume that exotic (and, more generally, multiquark) hadrons are mainly generated from many-quark partonic configurations, which may emerge either as short-term fluctuations of initial hadrons in any hadronic process, or as hadron remnants in hard processes (which are usually considered to be just remnants of the short-term fluctuations). Usually, manifestations of short-term fluctuations (or, of higher Fock components) of the initial hadron(s) are related with such hard hadronic processes as DIS, Drell-Yan pair, and/or high-p_T

[4]Note that hard processes, directly related to the short-term fluctuations, also have small cross sections, in comparison with soft processes. Separation of a hard process from much more copious soft background requires some special selection conditions, e.g., high-p_T or high-Q^2 events.

hadron production, and some others. Our hypothesis is a generalization of the suggestion of Karliner and Lipkin [35,36], who assumed the Θ^+-production mainly going through a special multiquark resonance. In difference, we do not stick to particular resonance(s) and admit contributions from any many-quark state.

If our hypothesis proves true, the multiquark production in processes with initial hadrons presents a new kind of hard processes, in addition to such familiar hard processes as DIS, high-p_T hadron production, Drell-Yan pair production, and so on. At first sight, they are essentially different: exotics production has not any continuous ''regulator'' of the hardness, which exists for many other processes (values of Q^2, p_T, Drell-Yan mass, and so on). However, in production of heavy quarkonium or heavy quark hadrons the hardness regulator is not continuous; it is fixed by the heavy quark mass. We expect that the characteristic time scale for production of multiquark hadrons should also be shorter than for soft production of the conventional hadrons. If this process is related indeed with higher Fock components, the exotics time scale should be somehow fixed by the minimal number of quarks in the exotic hadron.

We have demonstrated above that our assumption is really able to explain, at least qualitatively, why the Θ^+ has been seen in some experiments and not in others. Moreover, it allows one to overcome seeming inconsistencies between experiments, which are similar at first sight, and to understand such peculiar features of positive experiments as, e.g., essential change of signal/background ratio with relatively small change of registration conditions.

We can further suggest new experiments that might be decisive to check (and hopefully confirm) existence of the Θ^+ and other multiquark hadrons. Most important for this purpose could be studies of the hadron remnants in hard processes. Up to now, structure and evolution of those remnants have not been experimentally investigated and/or theoretically understood.

If our assumptions appear correct, experiments with production and investigation of multiquark hadrons could provide new, very interesting and important information about structure of conventional hadrons and about properties of their short-term fluctuations. In particular, it might help to understand structure and properties of higher Fock components for both conventional and multiquark hadrons.

Studies of multiquark hadrons will reveal, of course, a new hadronic spectroscopy, unobserved until now. They may also give a fresh look at constituent quarks. As is known, the constituent quarks are absent in the QCD Lagrangian, they emerge only as efficient objects (possibly, similar to quasiparticles in solid-state physics). Properties of such objects may depend on the environment. Therefore, the effective masses and couplings of the constituent quarks might be different in the conventional hadrons and in multiquark ones. If this phenomenon were discovered, it would strongly advance understanding the nature of the constituent quarks.[5] All the above prospects are only examples of the progress that could be related with exotic hadrons.

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