Experimental indication on chiral symmetry restoration in meson spectrum

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Abstract

The spectroscopic predictions of the Ademollo-Veneziano-Weinberg dual model are critically tested in view of the modern experimental data. The predicted equidistance of masses squared for chiral partners is shown to be violated high in energies, instead one observes an approximate degeneracy of these quantities. This phenomenon can be interpreted as the restoration of Wigner-Weyl realization of chiral symmetry for highly excited states. The scale of complete restoration is expected to be 2.5 GeV. A multispin-parity cluster structure of meson spectrum is revealed.

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1 Introduction

The problem of parity doubling in the spectrum of high "radial" excitations of light hadrons has been actively discussed recently [1–9]. One often relates this phenomenon to the Chiral Symmetry Restoration (CSR) at high energies (see, e.g., [10–13]) which is spontaneously broken at low energies. Namely, the typical scale of Chiral Symmetry Breaking (CSB) is $\Lambda_{\text{CSB}} \approx 1 \text{ GeV}$. Below this scale the chiral symmetry is known to be realized nonlinearly (the Nambu-Goldstone realization). But above this scale the linear (Wigner-Weyl) realization of chiral symmetry is expected to be restored. Since the chiral symmetry of QCD Lagrangian is almost exact in the light quark sector, an experimental signal for CSR should be approximate degeneracy of masses of chiral partners among light mesons above 1 GeV. Thus, investigations of parity doubling (both experimental and theoretical) are expected to shed some light on the phenomenon of CSB in QCD.

CSR in meson spectrum was predicted by the QCD sum rules [5,6,14,15] and some effective models [16]. On the other hand, the possibility of such phenomenon was criticized in [2,4] (within the sum rules in [1,9]). In particular, there exist other explanations for parity doubling (for a review see [17],
in the baryon sector see [2, 7]). The experimental status of parity doubling is still ambiguous. While in the baryon sector the situation is more or less certain (see, e.g., [7]), in the meson sector the data are rather scarce to see the effect distinctly. However, some time ago the analysis of the experimental data of Crystal Barrel Collaboration was published [18] where many new meson resonances were revealed. The obtained results were systematized in [19, 20]. The comprehensive review is contained in [21]. The experimental spectrum turned out to be very similar to the spectrum typically given by effective boson string theories.

In this Letter we show that the obtained in [18–20] data are consistent with CSR. As an auxiliary tool we will exploit the Ademollo-Veneziano-Weinberg dual model [22].

The paper is organized as follows. In Section 2 we argue that the available experimental data favour CSR at high energies. Section 3 is devoted to some discussions. The conclusions are summarized in final Section 4.

2 Phenomenological analysis

Let us discuss first the relation between CSR and parity doubling. In the relativistic theories one always deals with \((\text{masses})^2\) which mark different representations of Lorentz group. Consequently, only these quantities appear in all theoretical results. If chiral symmetry is restored parity doublets fall into multiplets of the chiral group with equal \((\text{masses})^2\) values [23]. Therefore, \textit{only approximate degeneracy of \((\text{masses})^2\) of chiral partners signalizes CSR in particle spectrum}. Thus, parity doubling is necessary but not sufficient condition for CSR. A practical consequence is that conclusions about CSR cannot be inferred from analysis of masses (as some authors do), one should analyze \((\text{masses})^2\). The reason is trivial: If the \((\text{masses})^2\) of chiral partners grow, say, as \(M_\pm^2(n) \sim n^\alpha (\alpha > 0)\) and the corresponding differences behave as \(M_\pm^2(n) - M_\mp^2(n) \sim n^\beta\) then at \(\beta < \frac{\alpha}{2}\) one always has the parity doubling high enough in energy in the sense \(M_\pm(n) - M_\mp(n) \xrightarrow{n \to \infty} 0\), while the \textit{genuine} CSR obviously requires \(\beta < 0\). At \(0 \leq \beta < \frac{\alpha}{2}\) one deals with the \textit{effective} CSR only.

Keeping in mind this distinction, let us proceed now to the experimental evidence for parity doubling in the sector of light mesons. Typically the evidences were based on some direct observations showing that opposite parity states cluster nearby in mass. However, it is often not clear which states are to be compared in channels with many states. This was a reason why such a naive treatment of experimental data was criticized in recent work [2], where a quite involved statistical method was proposed measuring the correlations.
between negative and positive parity states. This method was applied then to baryons and a significant signal for parity doubling in the non-strange baryons was revealed. From this work, however, we cannot judge whether there is a signal for CSR as only correlations between masses (not masses squared) were measured. In addition, in the baryon sector the parity doubling can be explained by restoration (or dynamical suppression) of axial symmetry only.

We would like to propose a much simpler theoretical construction for checking parity doubling and CSR in the light meson sector. In order to see which states are chiral partners one can use some phenomenologically successful model describing the meson spectrum. Comparing the predictions of this model with the experimental data, it may be possible to assess the parity doubling. In our opinion, the best candidate for the light meson sector is the dual resonance model proposed by Lovelace and Shapiro in [24] and generalized by Ademollo, Veneciano and Weinberg (AVW) in [22]. The spectrum of this model is depicted in Fig. 1. A characteristic feature of this spectrum is that (masses)$^2$ of chiral partners always have a constant shift (equal to $m^2_{\rho}$), i.e. in this case we have an effective parity doubling high in spectrum because

$$M_+(n) - M_-(n) = \frac{m^2_{\rho}}{M_+(n) + M_-(n)} \to 0, \quad n \gg 1.$$  \hspace{1cm} (1)

As discussed above, such an effective mass degeneracy high in spectrum is not a signal for CSR.

We analyzed all available spectroscopic data and depicted it in the same plot. After excluding all mesons with a large admixture of strange quark (which is seen from the corresponding decay channels) each experimentally detected state can be confronted with the one predicted by the model. We have found only a few exceptions: extra-states $\rho(1900)$, $\rho(2150)$, $f_2(1565)$, $f_2(1810)$ and missing ground scalar meson. The existence of additional states in $(I, J^{PC}) = (I, 1^{--}), (I, 2^{++}), ...$ channels is well known. In terms of the non-relativistic language their appearance is due to the fact that these states can be created by different orbital momenta [19], i.e. there exist not only S-wave vector and P-wave tensor mesons but also D-wave vector and F-wave tensor states. In the relativistic theories this seems to be related with the existence of two interpolating currents for the corresponding states [11]. The both candidates for the lightest scalar state, $f_0(600)$ and $f_0(980)$ mesons, seem not to be genuine quark-antiquark $SU_f(2)$ states (see note on scalar mesons in Particle Data Group [25]). Thus, we refrain from placing them on the trajectory.
Figure 1: The Regge trajectories predicted by the AVW spectrum [22] in units of $M^2_{\rho(770)}$: $\rho$-meson trajectory with daughters (solid lines) and $\pi$-meson trajectory with daughters (dashed lines). The predicted states are denoted by open circles and squares correspondingly. The filled circles and squares represent the corresponding averaged experimental values. The following experimental $J^P$ states were used [25] (the states discovered in analysis [18, 20] are marked by star). $0^+$(f$_0$-mesons): ?, 1350 $\pm$ 150, 1770 $\pm$ 12(*), 1992 $\pm$ 16, 2320 $\pm$ 30(*); $0^-$($\pi$-mesons): 140, 1300 $\pm$ 100, 1812 $\pm$ 14, 2070 $\pm$ 35(*), 2360 $\pm$ 30(*); $1^-$($\rho$-mesons): 775.8 $\pm$ 0.5, 1465 $\pm$ 25, 1720 $\pm$ 20, 1980 $\pm$ 30(*), 2265 $\pm$ 40(*); $1^+$(a$_1$-mesons): 1230 $\pm$ 40, 1647 $\pm$ 22, 1930$^{+30}_{-20}$(*), 2270$^{+55}_{-40}$(*); $2^+$(f$_2$-mesons): 1275 $\pm$ 1, 1638 $\pm$ 6, 1945 $\pm$ 13, 2240 $\pm$ 30(*); $2^-$($\pi_2$-mesons): 1672 $\pm$ 3, 2005 $\pm$ 15(*), 2245 $\pm$ 60(*); $3^-$($\rho_3$-mesons): 1686 $\pm$ 4, 1980 $\pm$ 15(*), 2250$\pm$?; $3^+$(a$_3$-mesons): 2030$\pm$20(*), 2275$\pm$35(*); $4^+$(f$_4$-mesons): 2034$\pm$11, 2300$\pm$?; $4^-$($\pi_4$-mesons): 2250 $\pm$ 15(*); $5^-$($\rho_5$-mesons): 2330 $\pm$ 35; $6^+$(f$_6$-mesons): 2465 $\pm$ 50.
As pointed out above, if the experimental states in Fig. 1 followed the prescribed positions we would have only effective parity doubling. The situation in the real world is, however, different: While the states with the quantum numbers of $\rho$-meson trajectory and its daughters tend to occupy the positions prescribed by the model, their chiral partners "glue" them the stronger the higher in energy the excitations are located. Other property of the experimental spectrum is that the states lying on the principal $\rho$-meson Regge trajectory have no chiral partners. These two features are general for channels with any spin and, consequently, they hardly can be accidental.

Effective parity doubling predicted by the model means that all states are equally influenced by CSB. In this case we observe parity doubling high in spectrum only because chirally non-invariant contribution to the masses remains constant while masses are growing, i.e. CSB effects become unimportant high in energy. Such a behavior was discussed within some approaches based on QCD sum rules [1, 26, 27]. Experimental spectrum depicted in Fig. 1 favours, however, another scenario: Chirally non-invariant contribution gradually decreases so that high in spectrum the $(masses)^2$ of chiral partners practically coincide within experimental accuracy. In other words, *experimental data favour a genuine CSR high in energy*.

A prominent feature of experimental spectrum, which we like to emphasize, is the existence of well-pronounced multispin-parity clusters of states, very similar to those observed in the baryon spectrum [28] (for a review see [7]). Namely, four such clusters are distinctively seen. The corresponding clustering occurs at $1350 \pm 120$, $1720 \pm 90$, $2000 \pm 70$, and $2300 \pm 60$ MeV with approximately the same mass gap between clusters, $m_{gap}^2 \approx (1080 \text{MeV})^2 \approx 2m_\rho^2$. The mass splitting within clusters is gradually decreasing high in energy. The clustering of mesons into narrow mass ranges was observed in a bit different aspect in [21].

### 3 Discussions

Let us try to figure out (at least intuitively) the origin of clusters in meson spectrum. To do this it is convenient to "switch off" two space dimensions and for a while do not bother about some nuances concerning the dynamics and the classification of states on parity. Then the spin degrees of freedom will disappear and the states in Fig. 1 will "collapse" to axis $0^\pm$. The AVW spectrum in this case can be written in the form $m^2(n) = m_\rho^2n$, with $n = 0, 1, 2, \ldots$, where the states alternate in parity. It resembles the asymptotics of dim2 QCD spectrum in the large-$N_c$ limit [29]. This spectrum is completely determined by the confinement forces (in dim2 there is
no spontaneous CSB but the massless pion exists). If we now "switch on" two additional space dimensions, each state then becomes \( 1 + (n + \delta_P)/2 \) times degenerate (here \( P = \pm 1 \) is parity and the Kronecker symbol was used) giving rise to a cluster of states. The permitted values for masses of excited states are still determined by confinement, but these values can be now obtained not only by exciting the ground state "radially" but also by exciting "orbitally". The spin interactions generate then a mass splitting within a cluster: Different spins have rather different "sensitivity" to CSB which occurs in dim4 QCD. Namely, the lower the spin is, the more sensitive it is to CSB (loosely speaking, as spin is a manifestation of quantum "inner motion", the faster this motion is, the less sensitive to the structure of vacuum it is). Fig. 1 is in agreement with such a intuitive picture: The masses of states with \( J = 0,1 \) typically reveal the largest deviations from the averaged mass within a cluster. Nevertheless, the splitting is less than the mass gap between the clusters which gives us a possibility to observe them. Another mentioned property of clusters in Fig. 1 is that the higher are the excitations the more pronounced cluster they form. This signals that the CSB effects gradually disappear high in energy. As a result we have \( M^2(n, J) \sim (n + J) \) for large enough \( n \) and \( J \). Such a behavior was predicted by the relativistic Nambu-Gotto open string (see, e.g., [30]) and by some effective string models (see, e.g., [31]). In addition, as was recently reported in [32], it can be given by AdS/QCD for vector and axial-vector mesons. However, these clusters are only multispin ones. What actually happens in reality (at least in the considered channels) is the multispin-parity clustering, i.e. \( M^2(P, n, J) = M^2(n + J) \). In terms of the linear ansatz it means that at large \( n \) and \( J \) one has \( M^2(P, n, J) = a(n + J) + b \) with universal slope \( a \) and intercept \( b \). It is the degeneracy of P-parity and/or chiral partners (they do not always coincide) which indicates on CSR. The AVW amplitude predicts the universal slope \( a = 2m^2_\rho \) which is fulfilled experimentally (this result was also derived within the QCD sum rules in [14, 27]). The universal intercept is very close to the value \( b = m^2_\rho \). As was shown in [14] such an intercept corresponds to a chirally-symmetric linear spectrum. This fact is another independent indication on the genuine CSR high in meson spectrum. However, CSR cannot completely describe the multispin-parity clustering since it does not predict the degeneracy of chiral multiplets with different spins. Some other symmetry is responsible for this phenomenon. Due to the Lorentz nature of spin the phenomenon might be explained by an appropriate grouping the mesons into some irreducible representations of Lorentz group (an example in the baryon sector is given in [33]).

A partial CSR is clearly observed at 1.7 GeV (position of the second cluster) and then CSR is rapidly progressing. If the tendency towards CSR
seen in Fig. 1 persists higher in spectrum than at $\Lambda_{CSR} \approx 2.5$ GeV (the position of the fifth hypothetical cluster) we should observe a complete CSR within the experimental errors. The same value for $\Lambda_{CSR}$ was obtained in framework of rather orthogonal approaches in [8, 34] (in the latter paper it was done for heavy-light quarkonia, but $\Lambda_{CSR}$ in that sector is expected to be the same). The physics above $\Lambda_{CSR}$ is indistinguishable from the physics of perturbative QCD continuum. The scale $\Lambda_{CSR}$ marks the transition from intermediate energy to high energy like the scale $\Lambda_{CSB}$ does from low to intermediate one. Thus, if experimentally confirmed, the scale $\Lambda_{CSR}$ is of a great importance because it marks the upper bound of resonance physics in the light quark sector of QCD. Theoretically it should be then considered as the third important scale in QCD. A practical consequence of the existence of this scale is that the most selfconsistent matching of finite energy sum rules and effective field models with QCD continuum can be achieved only at $\Lambda_{CSR}$.

Why the AVW amplitude does not work for the daughter trajectories? A qualitative answer which we could propose is that this amplitude is a low-energy approach by construction. Successfully describing the low-energy theorems of current algebra it fails at higher energies where the physics is different. The spectrum of light mesons in that region is well described by the effective string theories. The very fact that the AVW amplitude (unlike the Veneziano one) does not correspond to any string indicates (although indirectly) that it cannot describe correctly the high-energy region. This example clearly shows that direct extrapolations of a low-energy description (where the pion exchange is of a high importance) to high energies (where the physics is determined by the gluon exchange which is chirally invariant) can lead to wrong conclusions about spectral properties of excited states. For this reason one should be careful with any statements forbidding CSR which are based on the language of the low-energy effective field theory (like in [4]).

The absence of parity doubling on the leading trajectory looks enigmatic. This fact is rather definite experimentally [35]. A theoretical explanation could be the following. The leading $\rho$-meson trajectory (together with pion) gives the main contribution into the AVW amplitude. Therefore, this amplitude is not very sensitive to the deviations of experimental spectrum for the daughter trajectories, thus permitting the parity doubling. Hence, the absence of parity doublets for the states on the leading trajectory seems to be a minimal price to pay in order to reconcile a good low-energy behavior of the amplitude with the possibility of parity doubling at higher energies.
4 Conclusions

In this Letter we have shown that spectra of baryons and mesons in the light quark sector have more similarities than one usually thinks. Namely, like baryons the meson states not only form parity doublets but also reveal a well pronounced multispin-parity clustering in the spectrum. These facts indicate that the phenomena seem to have a unique origin. The rate of parity doubling in the spectrum of light mesons is consistent with a genuine chiral symmetry restoration (not only effective) occurring at $\Lambda_{CSR} \approx 2.5$ GeV. The scale $\Lambda_{CSR}$ is a new important scale in QCD which supplements $\Lambda_{CSB}$, i.e the chiral symmetry breaking phenomenon should be characterized by two scales. Because of chiral symmetry restoration the Ademollo-Veneziano-Weinberg dual amplitude fails in describing the daughter trajectories. Further experimental search for new light meson resonances is indispensable for confirmation of above conclusions.

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