Implications of the Crystal Barrel data for meson-baryon symmetries

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Abstract

Making use of numerous resonances discovered by the Crystal Barrel Collaboration we discuss some possible relations between the baryon and meson spectra of resonances composed of the light non-strange quarks. Our goal is to indicate new features that should be reproduced by the realistic dynamical models describing the hadron spectrum in the sector of light quarks.

The observation of more than thirty new inelastic $\bar{p}p$ resonances in the recent analyses of Crystal Barrel and PS172 data [1–4] has been a spectacular event in the spectroscopy of light hadrons below 2.4 GeV. It is well known that the hadron mass spectrum contains an important information on properties of the strong interactions. In this regard the data obtained remarkably confirmed various spectral regularities that indicate to a high degree of symmetry emerging in the large distance strong interactions [5–11]. And what is more the concept of Regge trajectories acquired a more solid experimental support. It is tempting to assume that instead of using the language of hadron resonances one could discuss some important phenomena in QCD, say the chiral symmetry breaking, in the language of geometrical behavior of Regge trajectories. We will try to demonstrate how the latter language may be used.

The purpose of this note is to bring attention to possible implications of the Crystal Barrel data for meson-baryon symmetries. We expect that the joint consideration of meson and baryon sectors could be useful for both sectors of hadron spectroscopy.

As a starting point for our discussions we present Fig. 1 where the combined meson-baryon light non-strange spectrum is displayed on one plot. For the details of meson plot we refer to [6], that plot is supplemented in Fig. 1 with the baryon states.

A prominent feature of light non-strange meson spectrum is the well-pronounced clustering of states near equidistant values of masses square [6–9]. The corresponding baryon sector is known to reveal a tendency to clustering

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as well. Our first observation is that the position of the third meson cluster happens to coincide with the first more or less pronounced cluster of baryons. Most of states in both clusters are well established [12], thus this is a quite secure effect. The resonances in the second baryon cluster (especially the well established ones) are shifted towards lower energies with respect to the fourth meson cluster. It seems that there is no enough data to speak about the next baryon cluster that would correspond to the fifth meson one.

These observations have important consequences for a possible dynamical supersymmetry that was suggested long ago [13]. Such a meson-baryon symmetry is commonly motivated by the quark-diquark structure of baryons where the diquark might have approximately the same constituent mass as quark and behave like antiquark in mesons. In particular, in ref. [14, 15] it is suggested that the diquarks can become well defined objects in the highly excited baryons due to large separation from the quark inside a baryon. The masses of some mesons and baryons are indeed surprisingly close. Unfortunately, such coincidences prove nothing because one should analyze the full amount of data. As seen in Fig. 1 near 1.7 GeV (the third meson cluster) some kind of meson-baryon supersymmetry can indeed take place. But the resonances obtained by the Crystal Barrel Collaboration (they mainly constitute the last two clusters in Fig. 1) do not confirm convincingly this symmetry. Even if one assumes that there are different kinds of diquarks (the spin singlet and spin triplet ones) with different masses and the constituent mass of diquarks depend on the energy scale, any meson-baryon symmetry should dictate a certain correlation between the number of mesons and baryons and this correlation should recur at higher energies. One indeed observes some recurrences in both meson and baryon sectors — the cluster structure of spectrum — but looking at the third and fourth meson clusters and their baryonic counterparts it is hard to see any clear-cut correlation in the number of states. It is not excluded of course that the reason is just a lack of data in the baryon sector.

In what follows we will indicate some new features of meson-baryon spectra that likely should be reproduced in any viable dynamical models describing the spectrum of light non-strange hadrons.

The recurrence patterns in meson spectrum seems to suggest that the MacDowell symmetry is (partly) realized in the meson sector. We will remind briefly the essence of this symmetry. Consider a Regge trajectory $\alpha(s)$. According to Regge-pole theory [16], in general there will be a series of daughter trajectories $\alpha_k(s)$ in the angular momentum plane, of alternating signature, satisfying

$$\alpha_k(s) = \alpha_0(s) - k, \quad k = 1, 2, \ldots$$

(1)
The MacDowell symmetry says that all baryon trajectories with equal isospin, the same signature, and opposite parity are degenerate. This property was indeed observed in the late 1960s [17, 18].

The meson spectrum also reveals the parity doubling and the Crystal Barrel data remarkably confirmed this phenomenon (see [11] for a review). A feature of meson trajectories is that the exchange degeneracy, resulting from the absence of $I = 2$ mesons [16], leads to the approximate coincidence of trajectories formed by $\rho$, $\omega$, $f_2$, and $a_2$ resonances. As a result, the $\rho$ ($\omega$) trajectory with $J = 1, 3, 5, \ldots$ and $a_2$ ($f_2$) trajectory of opposite signature with $J = 2, 4, 6, \ldots$ coalesce into one master trajectory (we recall that a reggeized pole amplitude of negative signature has poles at odd $J$ and that of positive signature does at even $J$). The equidistant sequence of daughters gives rise to linear "radial" trajectories — the towers of states with the same quantum numbers, the "radial" excitations in the language of potential models. For instance, the $J = 1$ states on the daughters of master trajectory have the quantum numbers of the $\rho$ ($\omega$) meson. In addition, the Adler self-consistency condition in dual models requires the master trajectory to have the intercept $a_0(m_\pi^2) = \frac{1}{2}$ and, hence, the slope $\alpha' = (2m_\rho^2 - 2m_\pi^2)^{-1}$ [16].

The results of Regge-pole theory are general consequences of unitarity and analyticity. The role of QCD is to provide the linearity of trajectories and the scale $\alpha'$. The corresponding trajectories are displayed in Fig. 2 and Fig. 3. The MacDowell trajectory pairs have to be joined at the point $M^2 = 0$, for convenience in representation the remaining trajectories are joined in a linear manner (like the baryon trajectories in ref. [17, 18]). We assign the experimental light unflavored states to the drawn trajectories according to their averaged masses and quantum numbers. The Crystal Barrel experiment revealed many new resonances in the energy interval 1.9 - 2.4 GeV, they occupy the vacant places in Fig. 2 and Fig. 3 with surprisingly high accuracy. In addition, in all cases when they do not coincide with the known states from the Particle Data Group (PDG) [12], the agreement with the theoretical expectations is improved. As a result one observes that all meson trajectories are approximately MacDowell symmetric except the leading master trajectory.

The first daughter of master trajectory and its MacDowell symmetric trajectory, the leading pseudoscalar one, show up an intriguing pattern of deviations from exact linearity for the low lying states (see Fig. 2 and Fig. 3). Presumably the deviations are caused by the chiral symmetry breaking (CSB) at low energies. It can be shown that the masses square of shifted states behave approximately as if the total length of joined trajectory remained unchanged after deviations, i.e. the joined trajectories are approximately "rigid" with respect to the strong interaction dynamics. In Fig. 2 and Fig. 3 we have confined ourselves by the linear form of deviations, but the conclusion holds
beyond this simplification. The observed correlations imply, in particular, that there may be a hidden relation between CSB and the violation of OZI-rule for scalar mesons (i.e. a considerable mixture of strange and non-strange components).

In Fig. 4 we display the spectrum of leading nucleon and delta trajectories and their daughters. The slopes of baryon and meson trajectories are known to coincide, for comparison we present in Fig. 4 the leading $\rho$-meson trajectory from Fig. 2. In addition, the leading nucleon and delta trajectories seem to coalesce into one baryon master trajectory. Similarly to the mesons, the leading delta trajectory does not possess the MacDowell symmetric pair, but this is not the case for the leading nucleon trajectory.

If an approximate symmetry between the meson and baryon spectra takes place it can provide new inside into the phenomenon of CSB. The deviations of trajectories from linearity at low energies are believed to be caused mainly by CSB in QCD. What happens to the spectrum of unflavored hadrons if we could somehow restore the chiral symmetry, maintaining the other features of confining QCD? One can naturally expect that the meson master trajectory remains almost unaffected as long as the mass of $\rho$-meson originates, most probably, from the QCD mass gap. On the other hand, in the case of exact meson-baryon supersymmetry, the leading baryon trajectories should coincide with the meson master trajectory (as seen from Fig. 4 in reality there is a constant shift between these trajectories, this fact is interesting by itself and is not yet understood). Since the intercept of the meson master trajectory is approximately $\frac{1}{2}$, the ground nucleon becomes massless in the chirally symmetric world. The fact that the mass of ground nucleon is mostly generated by CSB in QCD, has been known for long ago [19, 20], we just emphasize its relation with a possible meson-baryon symmetry. In addition, assuming a similar pattern of deviation from linearity as in the meson sector, one can immediately see from Fig. 4 why the ground nucleon state does not have a parity partner — the latter becomes tachyon after CSB and disappears from the physical spectrum. A dynamical description of this mechanism is a challenge for models describing CSB and hadron spectrum.

Another novel indication on the possible existence of meson-baryon symmetry could be the fact that the light non-strange spectrum of both mesons and baryons is, in a group-theoretical sense, similar to the spectrum of the hydrogen atom, but this is a subject of a separate paper [21].

Concluding this note, we hope that a new way of representation of data on light non-strange hadrons proposed here and ensuing new features of spectra will rise interest to the related problems both from the theoretical and from the experimental side.

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Figure 1: The spectrum of light non-strange hadrons in units of $M_{\rho(770)}^2$. The data for mesons is taken from refs. [12] and [3] (for the last two clusters) and for baryons from ref. [12]. Experimental errors are indicated except the one- and two-star baryons (by thin strips for $\Delta$). Circles stay when errors are negligible. For mesons the dashed lines mark the mean (mass)$^2$ in each cluster of states (these lines are continued to the baryon sector) and the open strips denote the one-star states from ref. [3] or the states that are dubious as non-strange mesons. The symbols ♦ and ◊ denote the two- and one-star nucleons correspondingly. The symbols ▼ and ▽ do the same for $\Delta$-baryons.
Figure 2: The trajectories of isovector non-strange mesons (in GeV^2). The filled circles (squares) denote the states contained in the PDG [12]. The open circles (squares) are the resonances observed in the Crystal Barrel experiment [3] (they are usually cited by the PDG in section "Further States"). The averaged values of masses are indicated in MeV and the experimental errors (if significant) are shown. The dashed line is the absent MacDowell pair for the leading master trajectory. The dotted line imitates the deviations presumably caused by CSB.
Figure 3: The trajectories of isoscalar non-strange mesons. The notations are as in Fig. 2.
Figure 4: The Regge trajectories of $N_{\frac{3}{2}^+}$ (squares) and $\Delta_{\frac{3}{2}^+}$ (circles) and their daughters. The experimental errors are indicated (for some states the Particle Data does not provide errors, in these cases we plot the whole range of masses reported for a given state, the ensuing errors are typically quite large). The leading $\rho$-meson trajectory from Fig. 2 is drawn for comparison. The dashed line is the MacDowell symmetric pair for the leading baryon trajectory. The dotted line shows a possible pattern of deviation from linearity at low energies for the leading nucleon trajectories.