Pentaquark decay is suppressed by chirality conservation

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It is shown, that if the pentaquark $\Theta^+ = uudd\bar{s}$ baryon can be represented by the local quark current η_Θ, its decay $\Theta^+ \to nK^+(pK^0)$ is forbidden in the limit of chirality conservation. The Θ^+decay width Γ is proportional to $\alpha_s^2\langle 0|\bar{q}q|0\rangle^2$, where $\langle 0|\bar{q}q|0\rangle$, $q = u, d, s$ is quark condensate, and, therefore, is strongly suppressed. The polarization operator of the pentaquark current is calculated using the operator product expansion. The Θ^+ mass found by the QCD sum rules method is in a reasonable agreement with experiment.

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Last year, the exotic baryon resonance Θ^+ with quark content $\Theta^+ = uudd\bar{s}$ and mass 1.54 GeV [1, 2] had been discovered. Later, the existence of this resonance was confirmed by many other groups, although some searches for it were unsuccessful. (see [3] for the review). Θ^+ baryon was predicted in 1997 by Diakonov, Petrov and Polyakov [4] in the Chiral Soliton Model as a member of antidecouplet with hypercharge $Y = 2$. The recent theoretical reviews are given in [5, 6]. Θ^+ was observed as a resonance in the systems nK^+ and pK^0. No enhancement was found in pK^+ mass distributions, what indicates on isospin $T = 0$ of Θ^+ in accord with theoretical predictions [4].

One of the most interesting features of Θ^+ is its very narrow width. Experimentally, only an upper limit was found, the stringer bound was presented in [2]: $\Gamma < 9$ MeV. The phase analysis of KN scattering results in the even stronger limit on Γ [7], $\Gamma < 1$ MeV. A close to the latter limitation was found in [8] from the analysis of $Kd \to ppK$ reaction and in [9] from K + Xe collisions data [2]. The Chiral Quark Soliton Model gives the estimation [4]: $\Gamma_{\rm CQSM} \lesssim 15$ MeV (Jaffe [10] claims that this estimation has a numerical error and in fact $\Gamma_{\rm CQSM} \lesssim 30$ MeV – see, however, [11]). In any way, the estimation [4] for $\Gamma_{\rm CQSM}$ follows from the cancellation of large and uncertain numbers and it is not quite reliable. Therefore, till now the narrow Θ^+ width is a theoretical puzzle.

We suggest here its qualitative explanation. Suppose, that Θ^+ may be represented by the local 5 quark current η_Θ. An example of such current is:

$$\eta_\Theta(x) = [\varepsilon^{abc}(d^a C\sigma_{\mu\nu}d^b)\gamma_\nu u^c \cdot \bar{s}\gamma_\mu\gamma_5 u - (u \leftrightarrow d)]/\sqrt{2}, \quad (1)$$

where a, b, c are color indeces, C – charge conjugation matrix, u, d, s – are quark fields. Suppose also, that the amplitude of $\Theta^+ \to nK^+$ decay is proportional to vacuum average

$$\mathcal{M} = \langle 0|T\{\eta_n(x), j_5^\lambda(y),\ \bar{\eta}_\Theta(0)\}|0\rangle \quad (2)$$

where $\eta_n(x)$ is the neutron quark current [12]

$$\eta_n = \varepsilon^{abc}(d^a C\gamma_\mu d^b)\gamma_5\gamma_\mu u^c \quad (3)$$

and $j_{\mu 5} = \bar{s}\gamma_\mu\gamma_5 u$ is the strange axial current. Let us neglect quark masses and perform the chiral transformation $q \to \gamma_5 q$. It is evident, that η_n and $j_{\mu 5}$ are even under such transformation, while η_Θ is odd. Therefore, the matrix element (2) vanishes in the limit of chiral symmetry. It is easy to see, that this statement is valid for any form of pentaquark and nucleon quark currents (spinless and with no derivatives). In the real world the chiral symmetry is spontaneously broken. The lowest dimension operator, corresponding to violation of chiral symmetry is $\bar{q}q$. So, the matrix element (2) is proportional to quark condensate $\langle 0|\bar{q}q|0\rangle$. Moreover, if Θ^+ is a genuine 5-quark state (not, say, the NK bound state), then in (2) the hard gluon exchange is necessary, what leads to additional factor of α_s. The necessity to have gluonic exchange in order to get nonvanishing value of $\mathcal{M}$ is confirmed by direct calculation of $\mathcal{M}$ for any η_Θ by the QCD sum rules (s.r.) method for three point function suggested in [13]. We come to the conclusion, that $\Gamma_\Theta \sim \alpha_s^2\langle 0|\bar{q}q|0\rangle^2$, i.e., Γ_Θ is strongly suppressed. This conclusion takes place for any genuine 5-quark states – the states formed from 5 current quarks at small separation, but not for potentially bounded NK-resonances, corresponding to large relative distances. There are no such suppression for the latters. In order to be confident that Θ^+ is described by the local 5-quark current η_Θ (1), calculate in QCD the polarization operator

$$\Pi(p) = i\int d^4x e^{ipx}\langle 0|T\eta_\Theta(x),\ \bar{\eta}_\Theta(0)|0\rangle \quad (4)$$

and demonstrate, that it may be represented by the contribution of Θ^+ and exited states (continuum). Consider $p^2 < 0$ and $|p^2|$ large enough, use the operator product expansion (OPE) and QCD s.r.method for baryons [12]. The Lorenz structure of $\Pi(p)$ has the form

$$\Pi(p) = \hat{p}\Pi_1(p^2) + \Pi_2(p^2), \qquad (5)$$

$\Pi_1(p^2)$ is calculated with the account of operators up to dimension 12, $\Pi_2(p^2)$ – up to dimension 13. Masses of u and d-quarks are neglected, the s-quark mass m_s is accounted in the first order. Factorization hypothesis is assumed for operators of higher dimensions, operators anomalous dimensions are neglected, as well as α_s corrections. On the other side, represent $\Pi(p)$ in terms of physical states contributions – Θ^+ and continuum, starting from some $(p^2)_0 \equiv s_0$. After Borel transformation the sum rules are given by

$$\frac{3M^{12}}{560}\left\{\frac{7}{6}E_5 + \left(\frac{7}{18}b - \frac{28}{3}m_s a\right)\frac{E_3}{M^4} - \frac{35}{18}\left[(5+8\gamma)a^2 - \frac{31}{4}m_s m_0^2 a\right]\frac{E_2}{M^6} + \frac{35}{6}\left(\frac{5}{2} + \frac{13}{3}\gamma\right)m_0^2 a^2 \frac{E_1}{M^8} + \left[\frac{560}{9}m_s a^3 - \frac{175}{48}(1+2\gamma)m_0^4 a^2 - \frac{35}{54}\left(19\gamma - \frac{3}{8}\right)ba^2\right] \times \frac{E_0}{M^{10}} + \frac{700}{27}(1.6\gamma - 0.2)\frac{a^4}{M^{12}}\right\} = \bar{\lambda}^2 e^{-m^2/M^2}, \qquad (6)$$

$$\frac{M^{10}}{32}a\left\{\frac{m_s}{10}M^2 E_5 - \frac{1}{5}(8-\gamma)E_4 + \frac{1}{12}(29 - 3\gamma)m_0^2\frac{E_3}{M^2} - \left[\left(\frac{9}{4} - \frac{17}{36}\gamma\right)b - 4m_s a\right]\frac{E_2}{M^4} + \left[8\left(\frac{4}{3} + \frac{1}{2}\gamma\right)a^2 - \frac{41}{6}m_s m_0^2 a\right]\frac{E_1}{M^6} - \left(14 + \frac{13}{3}\gamma\right)m_0^2 a^2 \frac{E_0}{M^8} + \left[\left(3 + \frac{131}{288} + \frac{37}{54}\gamma\right)m_0^4 a^2 - \frac{112}{9}m_s a^3\right]\cdot\frac{1}{M^{10}}\right\} = \bar{\lambda}^2 m e^{-m^2/M^2}, \qquad (7)$$

where m is the Θ^+-mass, M is the Borel parameter $(q = u, d)$,

$$a = -(2\pi)^2\langle 0|\bar{q}q|0\rangle, \ \gamma = \langle 0|\bar{s}s|0\rangle/\langle 0|\bar{q}q|0\rangle,$$

$$b = (2\pi)^2\langle 0|\frac{\alpha_s}{\pi}G^2|0\rangle,$$

$$g\langle 0|\bar{q}\sigma_{\mu\nu}(\lambda^n/2)G^n_{\mu\nu}q|0\rangle \equiv m_0^2\langle 0|\bar{q}q|0\rangle, \qquad (8)$$

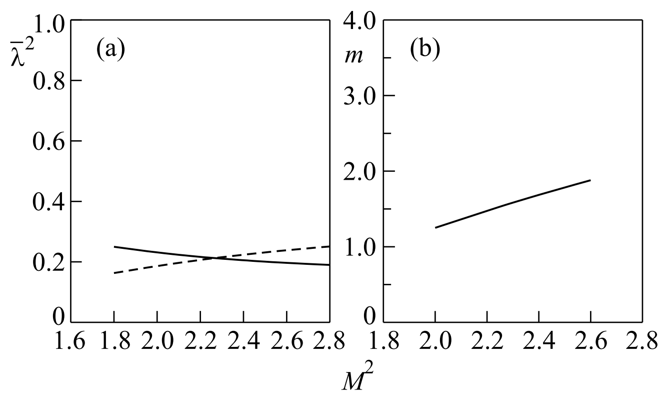
and the sign of g is defined by the form of covariant derivative $\nabla_\mu = \partial_\mu - ig(\lambda^n/2)A^n_\mu$, $\bar{\lambda}$ is given by the matrix element

$$\langle 0|\eta_\Theta|\Theta^+\rangle = \lambda v_\Theta, \qquad (9)$$

where v_Θ is Θ^+ spinor, $\bar{\lambda}^2 = (2\pi)^8\lambda^2$. Continuum contributions are transferred to the left-hand sides (l.h.s) of the s.r. resulting in appearance of the factors

$$E_n\left(\frac{s_0}{M^2}\right) = \frac{1}{n!}\int\limits_0^{s_0/M^2} dz z^n e^{-z}. \qquad (10)$$

The values of $\bar{\lambda}$, determined from eqs.(6) and (7) are plotted in Figure (Fig.(a), for m the experimental value of $m_\Theta = 1.54$ GeV was put in), and the



The M^2 dependence of the sum rules (6), (7): (a) $\bar{\lambda}^2$ from Eq.(6) – solid line, $\bar{\lambda}^2$ from eq.(7) – dashed line; (b) m obtained as a ratio of (7) to (6)

value of m obtained as a ratio of (7) to (6). The parameters were taken in accord with the recent determination of QCD condensates [14, 15] at normalization point $\mu^2 = 2\,\mathrm{GeV}^2$: $a = 0.63\,\mathrm{GeV}^3$, $b = 0.24\,\mathrm{GeV}^4$, $m_0^2 = 1\,\mathrm{GeV}^2$, $m_s = 0.15\,\mathrm{GeV}$, $\gamma = 0.8$. It was chosen $s_0 = 4.5\,\mathrm{GeV}^2$. As is seen from Fig.(a) the values of $\bar{\lambda}^2$ obtained from (6) and (7) weakly depend on M^2 and coincide with one another in the interval $2.0 < M^2 < 2.6\,\mathrm{GeV}^2$. The value of m_Θ may be estimated as $m_\Theta = 1.6 \pm 0.2\,\mathrm{GeV}$. The positivines of the l.h.s of (7) clearly shows that the parity of Θ^+ is positive. The result only slightly varies at the variation of s_0 within 10–15%.

Few remarks are in order. The first term in (1) contains two left $d_L d_L$ or two right $d_R d_R$ quark components, while the neutron current η_n (3) is proportional to $d_L d_R$ (see [12], Eq.61). Therefore, in the chiral limit two-hadron reducible contributions [16] are absent in the case of the η_Θ current (1). The same conclusion follows from opposite chiralities of the currents η_Θ and η_n. The inspection of the s.r.'s shows, that the main contributions arise from operators of high dimensions ($d = 6, 8$ in (6) and $d = 5$, 9, 11 in (7)), unlike the case of normal hadrons, where low dimension operators are dominant. This means, that pentaquark indeed differs very much from usual hadrons. There is a remarkable cancellation in (6) and (7) among the contributions of various operators. Therefore, the results are sensitive to unaccounted corrections (violation of factorization, α_s corrections erc.). So, not a quite good fulfillment of the s.r.'s is not surprising.

The QCD s.r.calculations of pentaquark masses with local η_Θ were pereformed in [17–19]. Unfortunately, nonsuitable chirally nonvariant 5-quark currents were chosen and the results change drastically after subtraction of two-hadron reducible contributions [16]. And besides, in [17] only one structure was considered and important terms of OPE were omitted.

The consideration of $\eta_\Theta^{T=1}$ current, corresponding to isospin $T = 1$ gives, that the s.r.(7) is essentially smaller than (6). So, in case of $T = 1$, there is no resonance structure at the masses 1.5–2.0 GeV, only a background more or less equally populated by the states of positive and negative parities (at the total angular momentum $j = 1/2$).

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