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THE $\eta_c \to p\bar{p}$ DECAY AND A QUARK-DIQUARK MODEL OF THE NUCLEON: THE CONTRIBUTION OF SCALAR-VECTOR DIQUARK TRANSITION

by

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ABSTRACT

The η_c decay into proton-antiproton cannot be explained by a lowest order perturbative QCD quark scheme. Trying to improve a previous result where diquarks were also considered as nucleon's constituents, the contribution of the spin-flip transition between scalar and vector diquarks inside the nucleon is computed and is shown to be strictly zero. This result excludes the possibility of understanding why this decay is experimentally observed with a branching ratio much greater than those of other charmonium decays into the same final state, $\chi_{0,1,2} \to p\bar{p}$, successfully described by pQCD in terms of quark and diquark components of the protons. A theoretical explanation of this decay rate is then still lacking and it is suggested that pseudoscalar glueballs might play an important role in solving the puzzle. The experimental results are also briefly discussed.

Key-words: Diquarks; Nucleon model; Mesonic decay.

In a recent paper [1] it was stressed that some hadronic decay modes of the η_c meson are not yet well understood in terms of elementary constituent dynamics, namely: $\eta_c \to \rho\rho$, $K^*\bar{K}^*$, $\phi\phi$ and $p\bar{p}$. The lowest order perturbative QCD scheme [2] is certainly reliable in the large Q^2 limit and it is argued to describe successfully the $\pi^+\pi^-$ and $\rho^+\rho^-$ decay channels of other $c\bar{c}$ mesons ($\chi_{0,2}$) with masses very close to that of the η_c [3]; however, it fails when applied to the above mentioned η_c decay modes and it has been shown that mass effects do not help [1]. Higher order Fock state components ($q\bar{q}g$) might help in the case of decays into final vector mesons [4], although a consistent treatment of all higher order corrections has never been attempted.

We shall consider here the $\eta_c \to p\bar{p}$ decay, which is strictly forbidden in the lowest order pQCD quark scheme, due to the helicity conservation of the gluon-quark couplings (in the limit of massless quarks) [3, 5]. Experimental data tell us that

$$\Gamma(\eta_c \to p\bar{p}) = (12.1 \pm 7.9)\ KeV \tag{1}$$

a value which is much larger than the decay rates for analogous processes which are not forbidden in the same scheme, $\Gamma(\chi_{0,1,2} \to p\bar{p})$ [6].

An attempt to improve the theoretical predictions for several charmonium decays into $p\bar{p}$ was made in former papers [5,7], considering diquarks as quasi-elementary baryonic constituents, in a natural generalization of the perturbative QCD scheme, as will be briefly described below. Such an assumption is supported by many experimental and theoretical arguments [8] suggesting that diquarks can be a useful way of modeling some non perturbative QCD corrections in an intermediate Q^2 scale. Actually, for such Q^2 values, several other exclusive processes are well described in the framework of a quark-diquark model for baryons, namely: the electromagnetic form factor of the nucleon [9], $\gamma\gamma \to p\bar{p}$ [10, 11] and Compton scattering [11]. Diquarks have also been introduced in some analysis of the nucleon structure functions in deep inelatic scattering [12, 13] and they have been shown to provide a natural explanation of some preliminary experimental results concerning the violation of the Gottfried sum rule [14]. The overall picture that emerges is one in which the nucleon is essentially made of a quark u, an almost pointlike scalar diquark ud, and of a small, but important, fraction of vector diquarks [5, 14].

The quark-diquark model of the nucleon allows to obtain, thanks to the vector diquark component, a non zero value for the $\eta_c \to p\bar{p}$ decay [5]. However, when considering a whole set of charmonium decays [7], $\eta_c, \chi_{0,1,2} \to p\bar{p}$, in order to fix all parameters of the model, it turns out that, while the χ decays can be described in good agreement with the existing experimental information, the value of $\Gamma(\eta_c \to p\bar{p})$ is much too small as compared with the experimental value [6,7]. It would then appear that the $\eta_c \to p\bar{p}$ decay, should the experimental very large result be confirmed, needs to proceed via a new mechanism, different from a pQCD component dynamics. Before concluding that, we study here the contribution of the scalar-vector diquark transition to this decay, not considered in Ref.[7]. It, in principle, might give a sizeable contribution to the decay, since, as we said before, scalar diquarks seem to be the dominant part of the nucleon wave function at an intermediate Q^2 scale.

A first claim for the existence of a transition between a vector and a scalar diquark emerged from the description of the magnetic moment of baryons in a static diquark model [15]. From a dynamical point of view, the spin-flip transition from a scalar to a vector diquark is shown to give a sizable contribution to the deep inelastic neutrino scattering [12]. However, a study of how this possibility could affect exclusive processes is still lacking.

The quark-diquark scheme is outlined here and the details can be found in Refs. [7,8]. In this scheme, diquarks are introduced as active constituents, while the general picture of a factorization between the elementary interaction amplitudes and the hadronization processes is maintained, as in the perturbative QCD scheme. The center of mass helicity amplitudes for the decay $\eta_c \to p\bar{p}$ are given by (all indices label helicities):

$$A_{\lambda_p,\lambda_{\bar{p}}}(\eta_c \to p\bar{p}) = \sum \int dx dy d^3k\, \psi^*_{p,\lambda_p}(y)\psi^*_{\bar{p},\lambda_{\bar{p}}}(x) \times \\ \times\; T_{\lambda_q\lambda_Q,\lambda_{\bar{q}}\lambda_{\bar{Q}};\lambda_c\lambda_{\bar{c}}}\, \psi_{\eta_c}(\vec{k})\, \delta_{\lambda_q+\lambda_Q,\lambda_p}\, \delta_{\lambda_{\bar{q}}+\lambda_{\bar{Q}},\lambda_{\bar{p}}} \qquad (2)$$

where the ψ's are the hadronic wave functions, the T's are the elementary helicity amplitudes for the constituent process $c\bar{c} \to qQ\bar{q}\bar{Q}$ (in the scheme where a nucleon is made of a quark q and a diquark Q) and the sum goes over all allowed quantum numbers of the constituents (colour, helicities and flavours). $\vec{k}$ is the relative momentum of the $c\bar{c}$ pair; Fermi motion is neglected in the final baryons and, therefore, the quark and diquark (antiquark and antidiquark) four-momenta are related to the momentum of the proton (antiproton) by, respectively, $Q = yp, q = (1-y)p$ ($\bar{Q} = x\bar{p}, \bar{q} = (1-x)\bar{p}$) and all masses are consistently taken into account.

The η_c wave function is taken as the nonrelativistic one

$$\psi_{\eta_c}(\vec{k}) = \frac{1}{\sqrt{4\pi}} \sqrt{\frac{\pi}{2}} R(0) \frac{1}{k^2} \delta(k) \frac{1}{\sqrt{2}} (c_+\bar{c}_+ - c_-\bar{c}_-) \tag{3}$$

where $R(0)$ is the value of the $c\bar{c}$ wave function at the origin (which can be fixed by fitting the data on $\eta_c \to \gamma\gamma$); the usual color part is not explicitely written here.

The SU(6)-like quark-diquark proton wave function is given by [10, 16]

$$\begin{aligned} \psi_{p,\lambda_p=\pm\frac{1}{2}}(y) = \frac{\pm F_N}{\sqrt{18}} \Big\{ & \phi_2(y) \left[2V_{\pm 1}(uu) d_{\mp} - \sqrt{2} V_{\pm 1}(ud) u_{\mp} \right] \\ & + \phi_3(y) \left[V_0(ud) u_{\pm} - \sqrt{2} V_0(uu) d_{\pm} \right] \\ & \pm \left[2\phi_1(y) + \phi_3(y) \right] S(ud) u_{\pm} \Big\} \end{aligned} \tag{4}$$

where $V_\lambda(ud)$ stands for a vector diquark made of a u and d quark with helicity λ and so on (S = scalar diquark). F_N is a constant (with the dimension of [mass]) whose squared modulus is related to the probability for the quark-diquark pair to hadronize into a proton. $\phi_{1,2,3}(y)$ are phenomenological diquark longitudinal momentum density distributions, normalized as $\int dx\, \phi_{1,2,3}(x) = 1$. Once the amplitudes A are computed, the decay rate is given by

$$\Gamma(\eta_c \to p\bar{p}) = \frac{(m_c^2 - m_p^2)^{1/2}}{64\pi^4 m_c} \sum_{\lambda_p,\lambda_{\bar{p}}} |A_{\lambda_p,\lambda_{\bar{p}}}(\eta_c \to p\bar{p})|^2 \tag{5}$$

where m_c is the constituent mass of the quark c and m_p is the proton mass.

The elementary helicity amplitudes corresponding, respectively, to a scalar diquark inside the proton and the vector one belonging to the antiproton $(V-S)$ and vice-versa $(S-V)$ are:

$$\begin{aligned} T^{(V-S)}_{\lambda_q 0,\lambda_{\bar q}\lambda_{\bar Q}\neq 0;\lambda_c\lambda_{\bar c}} &= -i4\sqrt{2}g_s^4 m_c^2 p^2 (2\lambda_c)(2\lambda_{\bar q}\lambda_{\bar Q}-1)\times \\ &\times \frac{xy(x-y)c_f G_T}{m_p g_1^2 g_2^2 (k^2-m_c^2)}\,\delta_{\lambda_c,-\lambda_{\bar c}}\delta_{\lambda_q,-\lambda_{\bar q}} \\ T^{(S-V)}_{\lambda_q\lambda_Q\neq 0,\lambda_{\bar q}0;\lambda_c\lambda_{\bar c}} &= -i4\sqrt{2}g_s^4 m_c^2 p^2 (2\lambda_c)(2\lambda_q\lambda_Q-1)\times \\ &\times \frac{xy(x-y)c_f G_T}{m_p g_1^2 g_2^2 (k^2-m_c^2)}\,\delta_{\lambda_c,-\lambda_{\bar c}}\delta_{\lambda_q,-\lambda_{\bar q}} \end{aligned} \tag{6}$$

For completeness, also the helicity amplitudes corresponding to the situation where only vector diquarks are involved are given below [5] *

$$\begin{aligned} T^{(V-V)}_{\lambda_q\lambda_Q\neq 0,\lambda_{\bar q}\lambda_{\bar Q}=0;\lambda_c\lambda_{\bar c}} &= i4\sqrt{2}g_s^4 m_c^2 p^2 (2\lambda_c)(\lambda_Q-2\lambda_q)\times \\ &\times \frac{x(x-y)c_f G}{m_p g_1^2 g_2^2 (k^2-m_c^2)}\,\delta_{\lambda_c,-\lambda_{\bar c}}\delta_{\lambda_q,-\lambda_{\bar q}} \\ T^{(V-V)}_{\lambda_q\lambda_Q=0,\lambda_{\bar q}\lambda_{\bar Q}\neq 0;\lambda_c\lambda_{\bar c}} &= -i4\sqrt{2}g_s^4 m_c^2 p^2 (2\lambda_c)(\lambda_Q-2\lambda_q)\times \\ &\times \frac{y(x-y)c_f G}{m_p g_1^2 g_2^2 (k^2-m_c^2)}\,\delta_{\lambda_c,-\lambda_{\bar c}}\delta_{\lambda_q,-\lambda_{\bar q}} \end{aligned} \tag{7}$$

In Eqs.(6,7), g_s is the strong coupling constant, G and G_T are diquark form factors, $c_f = 2\sqrt{3}/9$ is the colour factor and

$$\begin{aligned} g_1^2 &= (x-y)^2 m_p^2 + 4xy m_c^2 \\ g_2^2 &= (x-y)^2 m_p^2 + 4(1-x)(1-y) m_c^2 \\ k^2 - m_c^2 &= (x-y)^2 m_p^2 + 2(2xy-x-y) m_c^2 \end{aligned} \tag{8}$$

* In Eqs.(6) and (7) we follow the same kinematical notations and spinor conventions as in ref.[7]; instead, the amplitudes given in Ref.[5] differ from Eq.(7) by the substitution $x \leftrightarrow (1-y)$ and by an overall $2m_c$ factor.

In obtaining Eq.(6) we have used the virtual gluon-scalar-vector diquark coupling:

$$\begin{aligned} T^{\mu}(g^*(q) \to V(p_1, \epsilon_1) + S(p_2)) \\ = g_s \epsilon_{\alpha\beta\gamma\mu}(p_1 + p_2)^{\alpha} p_1^{\beta} (\epsilon_1^{\gamma})^* \frac{G_T(q^2)}{m_p} \end{aligned} \tag{9}$$

where we have written the $S-V$ transition form factor as $G_T(q^2)/m_p$, so that $G_T(q^2)$ is dimensionless. In Eq.(9) we have not written (as it does not play any role in the sequel) the usual $SU(3)$ colour factor.

It is straightforward to see that the substitution of Eqs.(6) into (2) yields a zero result, due to the fact that these elementary amplitudes are completely antisymmetric under the exchange of x and y: thus only the $T^{(V-V)}$ amplitudes contribute to $\Gamma(\eta_c \to p\bar{p})$. We can then conclude that the spin-flip transition between scalar and vector diquarks inside the nucleon cannot improve the theoretical prediction for the η_c decay rate (a factor $\sim 10^{-4}$ smaller than the experimental value) obtained by substituting Eqs. (3,4,7) into Eqs.(2,5) [7].

It seems we have to face the fact that the existing experimental value of $\Gamma(\eta_c \to p\bar{p})$ [6] poses a severe challenge to perturbative QCD decay mechanisms. As we said, the pure quark scheme [2] predicts, at lowest order, the decay to be zero and a quark-diquark model of the nucleon, although it gives a non zero result [5], leads, in a consistent treatment of a whole set of charmonium decays [7], to a value much smaller than the observed one. We have just seen that scalar-vector diquark transitions do not help and we also expect mass [5] and higher order corrections to the quark scheme not to be able alone to solve the problem.

Before considering possible alternative decay schemes let us make few comments on the experimental information we have [6]. The $\eta_c \to p\bar{p}$ decay has been observed in $J/\Psi \to \gamma p\bar{p}$ decays with a measurement of the $p\bar{p}$ effective mass distribution and the published value for the branching ratio is based on a very limited number of events. This explains the large errors in Eq.(1), which should not be forgotten and should caution us from drawing premature definite conclusions.

In case, however, that the experimental data [6] should be confirmed, one has to understand which decay mechanism would lead to such a large result. It is tempting to advocate for the $\eta_c \to p\bar{p}$ decay the same argument introduced in a similar situation, the so called $J/\Psi(\Psi') \to \rho\pi$ puzzle [17]. In such a case the decay would be enhanced by a quantum mechanical mixing of the η_c with a $J^{PC} = 0^{-+}$ gluonium state with a mass close to that of the η_c. A similar admixture has been studied for the ι meson [18]. We also remind that QCD sum rule arguments [19] estimate the pseudoscalar glueball mass to be within $2 - 2.5\,GeV$ [20]. Such an explanation would be confirmed, analogously to the $J/\Psi(\Psi') \to \rho\pi$ case [17], by data on $\eta_c' \to p\bar{p}$, if $B(\eta_c' \to p\bar{p})/B(\eta_c \to p\bar{p})$ turns out to be much smaller than 1.

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