Properties of the quark-antiquark-gluon Fock state in the $\eta_c$ meson

V.V. Braguta

1Institute for High Energy Physics, Protvino, Russia
2Institute for Theoretical and Experimental Physics, Moscow, Russia

In this paper the twist-3 distribution amplitude of the quark-antiquark-gluon Fock state in the $\eta_c$ meson is studied. To calculate the moments of this distribution amplitude QCD sum rules is applied. Using the results of the calculation the model of this distribution amplitude is built. In addition NRQCD matrix elements which determine the properties of the quark-antiquark-gluon Fock state are determined. In particular, the probability amplitude to find the quark-antiquark pair in the color octet state, the mean gluon energy and the fraction of momentum carried by gluon, the relative velocity of the color-octet quark-antiquark-pair are calculated.

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I. INTRODUCTION.

Theoretical description of hard exclusive processes is based on the factorization theorem [1, 2]. Within this theorem the amplitude of hard exclusive process can be separated into two parts. The first part is partons production at very small distances, which can be treated within perturbative QCD. The second part is hardronization of the partons at larger distances. This part contains information about nonperturbative dynamic of the strong interactions and it can be parameterized by process independent distribution amplitudes (DA), which can be considered as wave functions of hadrons at light-like separation between the partons.

Recently, two-particle charmonia DAs have become an object of intensive study [3–14]. Research in this direction allowed one to build models for two-particle charmonia DAs and to carry out the study of some interesting exclusive processes with charmonia production (see, for instance, [15–17]).

The first aim of this paper is to study the properties of the twist-3 quark-antiquark-gluon DA of the $\eta_c$ meson within QCD sum rules and to build the model of this function which can be used in the calculation of different production processes. There are a lot of papers (see, for instance, [2, 18, 19]) devoted to the study of the quark-antiquark-gluon Fock state DAs of light pseudoscalar mesons. However, until now there are no papers devoted to the study of similar DAs for charmonia.

Another description of charmonia production processes, which is called nonrelativistic QCD(NRQCD), is based on the expansion of matrix elements in powers of the relative velocity of quark-antiquark pair inside charmonia mesons [20]. NRQCD matrix elements play crucial role in this approach. These matrix elements parameterize charmonia structure. For instance, there is the matrix element which determines the probability amplitude to find quark-antiquark pair in the color-octet state in the $\eta_c$ meson. Another example is the matrix element which determines the gluon energy in the $\eta_c$ meson. The second aim of this paper is to determine some of these matrix elements from the quark-antiquark-gluon DA of the $\eta_c$ meson.

This paper is organized as follows. In the next section the definition of the twist-3 quark-antiquark-gluon DA will be given. The parameters of this DA will be calculated in the third section. The forth section is devoted to the calculation of the NRQCD matrix elements which parameterize the quark-antiquark-gluon Fock state in the $\eta_c$ meson. In section V the model of the DA under consideration will be proposed. In the last section the results of this paper will be summarized.

II. DEFINITION.

The twist-3 distribution amplitude (DA) of the quark-antiquark-gluon Fock state in the $\eta_c$ meson can be defined as follows [18, 19]

$$
\langle \eta_c(p)|\bar{q}(z)|\bar{q}(vz)\sigma^{\mu\nu}\gamma^5 g G_{\alpha\beta}(vz)|0\rangle_Q = i f_{\eta_c} \left( p_\alpha p_\mu g_{\nu\beta} - p_\alpha p_\nu g_{\mu\beta} - p_\beta p_\mu g_{\nu\alpha} + p_\beta p_\nu g_{\mu\alpha} \right) \times
\times \int dx_1 dx_2 dx_3 \delta(x_1 + x_2 + x_3 - 1)e^{i(pz)(x_1 - x_2 + x_3)}V_Q(x_1, x_2, x_3),
$$

*Electronic address: braguta@mail.ru*
where $V_Q(x_1, x_2, x_3)$ is the twist-3 DA of the quark-antiquark-gluon Fock state, $x_1, x_2, x_3$ are the fractions of momentum of the $\eta_c$ meson carried by the quark, antiquark and gluon correspondingly,

$$g_{\mu\nu}^\perp = g_{\mu\nu} - \frac{p_\mu z_\nu + p_\nu z_\mu}{pz},$$

$$[z_1, z_2] = P \exp \left( ig \int_{z_1}^{z_2} dz^\mu A_\mu \right).$$

Below it will be assumed that the function $V_Q(x_1, x_2, x_3)$ is normalized as follows

$$\int dx_1 dx_2 dx_3 \delta(x_1 + x_2 + x_3 - 1)V_Q(x_1, x_2, x_3) = 1$$

(2)

The DA $V_Q(x_1, x_2, x_3)$ is defined at the renormalization scale $Q$. The renormalization properties of three-particles DAs are rather complicated and they will not be discussed in this paper. For this reason below the subscript $Q$ will be omitted. It is worth to note that if the energy scale tends to infinity $Q \to \infty$, the DA $V_Q(x_1, x_2, x_3)$ tends to it’s asymptotic form

$$V_{as}(x_1, x_2, x_3) = 360x_1x_2x_3^2.$$  

(3)

Because of nonrelativistic nature of heavy quarkonia, one can expect that real DA is very far from its asymptotic form.

Another very useful property of the DA is that the function $V(x_1, x_2, x_3)$ is symmetric under the replacement $x_1 \leftrightarrow x_2$:

$$V(x_1, x_2, x_3) = V(x_2, x_1, x_3).$$  

(4)

Below we will also need the relation between the moments of the DA $V(x_1, x_2, x_3)$ and QCD matrix elements

$$2if_{3q}(pz)^{n_1+n_2+n_3+2}\langle x_1^{n_1}, x_2^{n_2}, x_3^{n_3} \rangle = \langle \eta_c(p)\{\vec{q}(i\vec{D})^{n_1}\} \sigma_{\mu\lambda} \gamma_5 \{g(i\vec{D})^{n_3}G_{\mu\nu}\} \{i\vec{D}\}^{n_2}q \} \rvert 0 \rangle \lambda^\lambda \lambda^\nu.$$  

(5)

The properties of the DA $V(x_1, x_2, x_3)$ can be parameterized by the moments $\langle x_1^{n_1}, x_2^{n_2}, x_3^{n_3} \rangle$. In this paper the following moments will be calculated $\langle x_3 \rangle, \langle x_3^2 \rangle, \langle (x_1 - x_2)^2 \rangle$. The other the first and the second moments can be expressed through these ones.

### III. THE MOMENTS OF THE DISTRIBUTION AMPLITUDE $V(x_1, x_2, x_3)$ FROM QCD SUM RULES.

QCD sum rules $[21, 22]$ proved to be very effective and universal tool in the determination of different matrix elements. In particular, QCD sum rules can be applied to study the properties of DAs. There are a lot of papers (see, for instance, $[2, 18, 19]$) where QCD sum rules was applied to study the parameters of the twist-3 DAs of light pseudoscalar mesons. However, there are no papers devoted to the study of heavy quarkonia DAs of the quark-antiquark-gluon Fock state.

In this section QCD sum rules will be applied to calculate the moments of the function $V(x_1, x_2, x_3)$. To do this let us consider the correlator

$$\Pi_{n_1,n_2,n_3}(q,z) = i \int d^4xe^{iqx} \langle 0|TJ_{n_1,n_2,n_3}^+(x,z)J_{0,0,0}(0,z)|0 \rangle = (zq)^{n_1+n_2+n_3+4}\Pi(q^2),$$  

(6)

where the current $J_{n_1,n_2,n_3}(x,z)$ is defined as follows

$$J_{n_1,n_2,n_3}(x,z) = \{\vec{q}(i\vec{D})^{n_1}\} \sigma_{\mu\lambda} \gamma_5 \{g(i\vec{D})^{n_3}G_{\mu\nu}\} \{i\vec{D}\}^{n_2}q \} \rvert \lambda^\lambda \lambda^\nu.$$  

(7)

Applying standard procedure which will not be described here one gets QCD sum rules for correlator $[8]$

$$4f_{3q}^2\langle x_1^{n_1}, x_2^{n_2}, x_3^{n_3} \rangle = \frac{1}{m^2} \int_{4m^2}^{s_0} ds \frac{\text{Im} \Pi_{\text{pert}}(s)}{(s+Q^2)^{m+1}} + \frac{1}{m!} \left(-\frac{d}{dQ^2}\right)^m \Pi_{\text{pert}}(Q^2),$$  

(8)

where $Q^2 = -q^2$, $\Pi_{\text{pert}}(s), \Pi_{\text{pert}}(s)$ are the perturbative and nonperturbative contributions to correlator $[8]$. The nonpertubative part of the correlator parameterizes the contribution of the vacuum condensates, which at the leading
order approximation used in this paper is given by the gluon vacuum condensate $\langle \alpha_s G^2 \rangle$. The expressions for the $\text{Im} \Pi_{\text{pert}}(s), \Pi_{\text{npert}}(s)$ are rather lengthy and very complicated. For this reason they will not be shown here.

In the original paper [22] the method QCD sum rules was applied at $Q^2 = 0$. However, as was shown in paper [22] there is a large contribution of higher dimensional operators at $Q^2 = 0$ which grows rapidly with $m$. To suppress this contribution in this paper sum rules [8] will be applied at $Q^2 = 4m^2$.

In the numerical analysis of QCD sum rules the values of the parameters $m_c$ and $\langle \alpha_s G^2 \rangle$ will be taken from paper [23].

$$m_c = 1.24 \pm 0.02 \text{ GeV, } \langle \frac{\alpha_s}{\pi} G^2 \rangle = 0.012 \pm 30\% \text{ GeV}^4.$$  

(9)

The value of the threshold $s_0$ is varied within the interval $\sqrt{s_0} \in (3.7 \pm 0.2) \text{ GeV}$. The value of the strong coupling constant is taken from paper [24]

$$\alpha_s(m_c) = 0.332 \pm 0.015,$$  

(10)

and then it is evolved to the scale $\mu = m_c$ at two loops. In the calculation the uncertainty of the results due to the variation of the strong coupling constant $\alpha_s$ is not very important. For this reason it will be disregarded.

The application of sum rules [8] to the calculation of the constant $f_{3n}$ gives the following result

$$f_{3n}^2 = (12 \pm 3 \pm 2 \pm 1) \cdot 10^{-6} \text{ GeV}^4,$$  

(11)

where the second, the third and the forth errors are due to the uncertainties in the values of the parameters $m_c$, $\langle \alpha_s G^2 \rangle$ [11] and $s_0$ correspondingly.

Further let us proceed to the calculation of the moments $\langle x_1^n x_2^m x_3^n \rangle$. The result of the calculation of the moment $\langle x_3 \rangle$ is

$$\langle x_3 \rangle = 0.22 \pm 0.01 \pm 0.01 \pm 0.02.$$  

(12)

The sources of errors are the same as in [11]. Evidently, due to the symmetry relation [4] the other first moments can be related to the $\langle x_3 \rangle$ as follows $\langle x_1 \rangle = \langle x_2 \rangle = (1 - \langle x_3 \rangle)/2$.

It should be noted that moment [12] has simple and very important physical meaning. The $\langle x_3 \rangle$ measures the fraction of momentum carried by gluon in the quark-antiquark-gluon Fock state of the $\eta_c$ meson. Value [12] tells us that the gluon carries $\sim 20\%$ of the total momentum.

Another moments which also have important physical meaning are $\langle (x_1 - x_2)^2 \rangle, \langle x_3^2 \rangle$. The calculation gives

$$\langle (x_1 - x_2)^2 \rangle = 0.021 \pm 0.002 \pm 0.003 \pm 0.001$$  

$$\langle x_3^2 \rangle = 0.055 \pm 0.005 \pm 0.006 \pm 0.004.$$  

(13)

The sources of errors are the same as in [11]. It is easy to show that all moments of the first and the second order can be expressed through moments [12], [13].

It should be noted here that matrix elements [11], [12], [13] are scale dependent quantities. The virtuality of the propagators in the calculation of the $\text{Im} \Pi_{\text{pert}}(s), \Pi_{\text{npert}}(s)$ is of order of $\sim m_c$. So, results [11], [12], [13] are defined at the same scale.

**IV. NRQCD MATRIX ELEMENTS AND PROPERTIES OF THE QUARK-ANTIQUARK-GLUON FOCK STATE IN THE $\eta_c$ MESON.**

As was noted in the introduction, the DA $V(x_1, x_2, x_3)$ contains the information about properties of the quark-antiquark-gluon Fock state in the $\eta_c$ meson. According to formula [5] this properties can be parameterized by some rather complicated QCD operators. To make the result of this paper more transparent, one can expand these operators in the relative velocity of the quark-antiquark pair in the $\eta_c$ meson, as was done in paper [5]. Following the approach proposed in this paper, at the leading order approximation one gets the relations

$$\langle \eta_c | \psi^+ \sigma_j (gH_j) \chi \rangle |0\rangle = 3 f_{3n} M_{\eta_c}^2,$$  

(14)

$$\langle \eta_c | \psi^+ \sigma_j (|i\vec{V}_0 gH_j\rangle) \chi \rangle |0\rangle = 3 f_{3n} M_{\eta_c}^2 \langle x_3 \rangle,$$  

(15)

$$\langle \eta_c | \psi^+ \sigma_j ((-3\vec{\nabla}_0 - \vec{\nabla}_k)gH_j) \chi \rangle |0\rangle = 9 f_{3n} M_{\eta_c}^2 \langle x_3^2 \rangle,$$  

(16)

$$\langle \eta_c | \psi^+ \sigma_j ((-\vec{\nabla}_k gH_j - gH_j \vec{\nabla}_k - \frac{3}{2} \vec{\nabla}_k gH_j \vec{\nabla}_k) \chi \rangle |0\rangle = 9 f_{3n} M_{\eta_c}^2 \langle (x_1 - x_2)^2 \rangle.$$  

(17)
where $\psi^+$ and $\chi$ are Pauli spinor fields that create a quark and an antiquark respectively, $\bar{\sigma}$ is the Pauli matrices, $\bar{H}$ is a chromomagnetic field, $j, k$ are spatial indexes. Note that in \[14]-\[17] summation over the repeated indexes is assumed.

From formulas \[14]-\[17] one sees that the quark-antiquark pair is in the $S$-wave spin-triplet color-octet state. The role of the color-octet state in the $\eta_c$ meson is determined by the matrix element

$$
\langle \eta_c| \psi^+ g(\bar{\sigma}\bar{H})|0\rangle = 3f_{3\eta}M_{\eta_c}^2 = (92 \pm 34) \cdot 10^{-3} \text{ GeV}^4.
$$

(18)

Note that in the last formula the uncertainty due to the higher order terms in the relative velocity expansion have been taken into account.

Strictly speaking, the role of the color-octet state in the $\eta_c$ meson strongly depends on the process. However, one can estimate the probability amplitude to find the color-octet state as follows

$$
\langle \bar{q}qG|\eta_c\rangle \sim \frac{\langle \eta_c| \psi^+ \sigma_j (gH_j) \chi|0\rangle}{m_c^2 \langle \eta_c| \psi^+ \chi|0\rangle} \sim 0.04.
$$

(19)

One sees that this value is very small. In paper \[25\] the ratio $\langle \bar{q}qG|\eta_c\rangle$ was estimated as $\sim v^{7/2} \sim 0.06 - 0.09$ for $v^2 \sim 0.20 - 0.25$, what is in reasonable agreement with result \[19\].

Now one can estimate the average fraction of momentum carried by gluon in the $\eta_c$ meson. To do this one can apply the standard quantum mechanical formula

$$
\langle x_g\rangle = \sum_f p_f \times \langle x_g\rangle_f,
$$

(20)

where the sum is taken over all Fock states $f$ in the $\eta_c$ meson, $p_f$ is the probability to find the Fock state $f$, $\langle x_3\rangle_f$ is the fraction of momentum carried by gluon in the Fock state $f$. Assuming that the dominant contribution to formula \[20\] is given by the quark-antiquark-gluon Fock state one gets $\langle x_g\rangle \sim 3 \cdot 10^{-4}$.

Further let us pay attention to formula \[14\]. This formula allows us to calculate the mean energy of the gluon in the $\eta_c$ meson

$$
E_g = \frac{\langle \eta_c| \psi^+ \sigma_j (i\vec{\nabla}_0 gH_j) \chi|0\rangle}{\langle \eta_c| \psi^+ \chi|0\rangle} = M_\eta \langle x_3\rangle = (0.66 \pm 0.18) \text{ GeV}.
$$

(21)

One can also estimate the gluon energy from formula \[19\]

$$
E_g \sim \sqrt{\frac{\langle \eta_c| \psi^+ \sigma_j (v^2 q_0 - \vec{\nabla}^2) gH_j \chi|0\rangle}{4\langle \eta_c| \psi^+ \chi|0\rangle}} = M_\eta \sqrt{\frac{3}{4} \langle x_3^2\rangle} = 0.61 \text{ GeV}.
$$

(22)

This value is in a good agreement with \[21\].

In the last excise the relative momentum $p_c$ of the color-octet quark-antiquark pair will be determined. To do this let us apply formula \[17\]

$$
|p_c| \sim \frac{1}{2(1 - \langle x_3\rangle)} \sqrt{\frac{\langle \eta_c| \psi^+ \sigma_j (\vec{\nabla}^2_k gH_j - 2\vec{\nabla}_k gH_j \vec{\nabla}_k) \chi|0\rangle}{\langle \eta_c| \psi^+ \chi|0\rangle}} = \frac{1}{2} \sqrt{\frac{3(\langle x_1 - x_2^2\rangle^2)}{(1 - \langle x_3\rangle)^2}} M_\eta = 0.49 \text{ GeV},
$$

(23)

It is important to note that the relative velocity of the color-octet quark-antiquark pair ($v_0^2 \sim 3\langle (x_1 - x_2^2)/\langle 1 - \langle x_3\rangle\rangle^2 ∼ 0.11$) is two times smaller than that for the color-singlet quark-antiquark state ($v_0^2 ∼ 0.21$ \[3\]). What is expected result since the gluon carries some fraction of momentum and energy of the $\eta_c$ meson.

### V. THE MODEL OF THE DISTRIBUTION AMPLITUDE $V(x_1, x_2, x_3)$

To build the model of the DA $V(x_1, x_2, x_3)$ one can recall that the models of the leading twist charmonia distribution amplitudes proposed in papers \[3, 6, 11\] can be written in the following form

$$
\phi \sim \phi_{as} \cdot \exp \left( - \frac{M_{as}^2}{M^2} \right),
$$

(24)
where $\phi_{as}$ is the asymptotic form of the distribution amplitude $\phi$, $M^2_{c\bar{c}}$ is the invariant mass of the $c\bar{c}$ system expressed in terms of kinematic variables, $M^2$ is the characteristic invariant mass of the $c\bar{c}$ system.

In the case of the quark-antiquark-gluon Fock state the $\eta_c$ meson can be divided into two subsystems: the quark-antiquark pair in the color-octet state and the color-octet pair with the gluon. If one introduces the following variable

$$x_1 = xy, \quad x_2 = (1-x)y, \quad x_3 = 1 - y,$$

(25)

the invariant masses of the corresponding subsystems can be written in the form

$$M^2_{c\bar{c}} = m_c^2 \frac{1}{x(1-x)} = m_c^2 \frac{(1-x)^2}{x_1 x_2}, \quad M^2_{(c\bar{c})g} = m_c^2 \frac{1}{xy(1-x)} = m_c^2 \frac{(1-x_3)}{x_1 x_2}.$$

(26)

To build the model of the DA $V(x_1, x_2, x_3)$ one should introduce the exponent factors for the both subsystems. Thus one has

$$V(x_1, x_2, x_3) = c(\beta_1, \beta_2)x_1 x_2 x_3^2 \cdot \exp\left(-\beta_1 \frac{(1-x_3)^2}{x_1 x_2}\right) \cdot \exp\left(-\beta_2 \frac{(1-x_3)}{x_1 x_2}\right),$$

(27)

where the constant $c(\beta_1, \beta_2)$ can be determined from normalization condition (2). The values of the parameters $\beta_1, \beta_2$ can be fixed from the requirement that the values of the moments $\langle x_3 \rangle, \langle (x_1 - x_2)^2 \rangle$ for model (27) must coincide with the values (12), (13). Thus one gets $\beta_1 = 1.25 \pm 0.65, \beta_2 = 1.15 \pm 0.25$. Note that model (27) is defined at the scale $\mu \sim m_c$.

One can assume that it is sufficient to introduce only one exponent with the total invariant mass of the quark-antiquark-gluon system in formula (27). However, the calculation shows that in this case it is not possible to reproduce values (12), (13) of the moments $\langle x_3 \rangle, \langle (x_1 - x_2)^2 \rangle$ simultaneously. Physically, this means that although energy scales of the two subsystems introduced above are of the same order they are not equal to each other.

VI. CONCLUSION

In this paper the properties of the quark-antiquark-gluon Fock state in the $\eta_c$ meson are studied. This properties can be parameterized by the moments of the twist-3 distribution amplitude (11) and the constant $f_{3\eta_c}$. To calculate the first, the second order moments and the constant $f_{3\eta}$ QCD sum rules was applied. The result of this calculation allowed one to build the model of the DA which can be used in the study of different production processes.

To make the results of the calculation more transparent, QCD operators which determine the moments of the distribution amplitude are expanded in relative velocity of the quark-antiquark pair in the $\eta_c$ meson. In particular, it was shown that the quark-antiquark pair is in the $S$-wave spin-triplet color-octet state. The probability amplitude to find the quark-antiquark pair in the color-octet state is rather small $\sim 0.04$. The energy of the gluon in the quark-antiquark-gluon Fock state is $\sim 600$ MeV. The relative velocity of the color-octet quark-antiquark pair is $\sim 0.11$ what is much smaller than that in the color-singlet quark-antiquark pair.

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