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A CORRECTION TO THE HAMILTONIAN OF THE QCD STRING WITH QUARKS DUE TO THE RIGIDITY TERM

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The action of the gluodynamics string, obtained in Ref.[1], is used for the derivation of the correction, arising due to the rigidity term, to the Hamiltonian of the quark-antiquark system, which was obtained in Refs. [2,3]. This correction contains additional contributions to the orbital momentum of the system and several higher derivative operators. With the help of the obtained Hamiltonian a rigid string-induced term in the Hamiltonian of the relativistic quark model is evaluated for the case of large masses of a quark and antiquark.

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1. In a recent paper [1] it was shown that the effective action of the gluodynamics string obtained from the expansion of the averaged Wilson loop $\langle W(C)\rangle$, written through the non-Abelian Stokes theorem [4,5] and cumulant expansion [5,6], has the form of a series in powers of T_g/L, where T_g is the correlation length of the vacuum, and L is the size of the Wilson loop. Keeping in the cumulant expansion only the lowest-bilocal term, which is dominant according to lattice data [7],

$$\langle W(C)\rangle = \mathrm{tr}\ \exp\left(-\int\limits_S d\sigma_{\mu\nu}(w)\int\limits_S d\sigma_{\lambda\rho}(w')\left\langle F_{\mu\nu}(w)\Phi(w,w')F_{\lambda\rho}(w')\Phi(w',w)\right\rangle\right),$$

and parametrizing it in the following way [7,8]

$$\left\langle F_{\mu\nu}(w)\Phi(w,w')F_{\lambda\rho}(w')\Phi(w',w)\right\rangle = \frac{1}{N_c}\left\{(\delta_{\mu\lambda}\delta_{\nu\rho}-\delta_{\mu\rho}\delta_{\nu\lambda})\,D\left(\frac{(w-w')^2}{T_g^2}\right)+\right.$$

$$+\frac{1}{2}\left[\frac{\partial}{\partial w_\mu}\left((w-w')_\lambda\delta_{\nu\rho}-(w-w')_\rho\delta_{\nu\lambda}\right)+\frac{\partial}{\partial w_\nu}\left((w-w')_\rho\delta_{\mu\lambda}-(w-w')_\lambda\delta_{\mu\rho}\right)\right]\times$$

$$\times D_1\left(\frac{(w-w')^2}{T_g^2}\right)\Bigg\},$$

where D and D_1 are two renormalization group invariant coefficient functions, one arrives at the following effective action of the gluodynamics string, induced by the nonperturbative background fields

$$S_{biloc.}=-\ln\langle W(C)\rangle=\sigma\int d^2\xi\sqrt{g}+\frac{1}{\alpha_0}\int d^2\xi\sqrt{g}g^{ab}\left(\partial_a t_{\mu\nu}\right)\left(\partial_b t_{\mu\nu}\right)+$$

$$+O\left(\frac{T_g^6}{L^2}\alpha_s \mathrm{tr}\left\langle F_{\mu\nu}^2(0)\right\rangle\right), \quad (1)$$

where

$$\sigma=4T_g^2\int d^2zD\left(z^2\right)$$

is the string tension of the Nambu–Goto term, and

$$\frac{1}{\alpha_0}=\frac{1}{4}T_g^4\int d^2zz^2\left(2D_1\left(z^2\right)-D\left(z^2\right)\right)$$

is the inverse bare coupling constant of the rigidity term. Here $\partial_a\equiv\partial/\partial\xi^a$; $a,b=1,2$; $g_{ab}=\left(\partial_a w_\mu\right)\left(\partial_b w_\mu\right)$ is the induced metric tensor, $g=\det\parallel g_{ab}\parallel$, $t_{\mu\nu}=(1/\sqrt{g})\varepsilon^{ab}\left(\partial_a w_\mu\right)\left(\partial_b w_\nu\right)$ is the extrinsic curvature of the string world sheet.

The aim of this letter is to apply action (1) to the derivation of the correction to the Hamiltonian of the quark-antiquark system in the confining QCD vacuum, which was obtained in Ref.[2] for the case of equal masses of a quark and antiquark and generalized in Ref.[3] to the case of arbitrary masses. Both in Refs.[2] and [3] only the Nambu–Goto term on the R.H.S. of Eq.(1) was accounted for in the expression for the Green function of the spinless $q\bar{q}$-system, written by virtue of the Feynman–Schwinger representation in the form

$$G\left(x\bar{x}|y\bar{y}\right)=\int\limits_0^\infty ds\int\limits_0^\infty d\bar{s}\int DzD\bar{z}\ e^{-K-\bar{K}}\left\langle W(C)\right\rangle, \quad (2)$$

where

$$K=m_1^2s+\frac{1}{4}\int\limits_0^s d\gamma\dot{z}^2(\gamma),\qquad \bar{K}=m_2^2\bar{s}+\frac{1}{4}\int\limits_0^{\bar{s}} d\gamma\dot{\bar{z}}^2(\gamma),$$

and our goal here is to consider also the rigidity term. Analogously to Ref.[3] we shall consider the $q\bar{q}$-system with arbitrary masses of a quark and antiquark.

In this way we shall work within the same approximations, which were used in [2,3], namely we shall disregard spin effects and the influence of additional quark loops. Secondly, we shall neglect quark trajectories with backward motion in the proper time, which might lead to creation of additional $q\bar{q}$-pairs.

Besides that, we shall use the straight-line approximation for the minimal surface S, that, as was argued in [2,3], corresponds to the valence quark approximation. Such a "minimal" string may rotate and oscillate longitudinally. This approximation is inspired by two limiting cases: $l=0$ and $l\to\infty$.

The first case will be then investigated in more details, and the correction to the Hamiltonian of the relativistic quark model [9] due to the rigidity term in the limit of large masses of a quark and antiquark will be derived.

The main results of the letter are summarized in the Conclusion.

2. A correction to the Hamiltonian of the "minimal" QCD string with spinless quarks due to the rigidity term. Making use of the auxiliary field formalism [2,10], one can represent Green function (2) with $\langle W(C)\rangle$ defined via Eq.(1) in the following way

$$G(x\bar{x}|y\bar{y}) = \int DzD\bar{z}D\mu_1 D\mu_2 Dh_{ab}\exp\left(-K'-\bar{K}'\right)\exp\left[(-\sigma+2\bar{\alpha})\int d^2\xi\sqrt{h}\right]\times$$

$$\times\exp\left[-\bar{\alpha}\int d^2\xi\sqrt{h}h^{ab}\left(\partial_a w_\mu\right)\left(\partial_b w_\mu\right)-\frac{1}{\alpha_0}\int d^2\xi\sqrt{h}h^{ab}\left(\partial_a t_{\mu\nu}\right)\left(\partial_b t_{\mu\nu}\right)\right], \qquad (3)$$

where we have integrated over the Lagrange multiplier $\lambda^{ab}(\xi) = \alpha(\xi)h^{ab}(\xi)+$ $+f^{ab}(\xi), f^{ab}h_{ab} = 0$, and $\bar{\alpha}$ is the mean value of $\alpha(\xi)$. Here $t_{\mu\nu} = \frac{1}{\sqrt{h}}\varepsilon^{ab}\times$ $\times\left(\partial_a w_\mu\right)\left(\partial_b w_\nu\right)$,

$$K'+\bar{K}' = \frac{1}{2}\int\limits_0^T d\tau\left[\frac{m_1^2}{\mu_1(\tau)}+\mu_1(\tau)(1+\dot{\mathrm{z}}^2(\tau))+\frac{m_2^2}{\mu_2(\tau)}+\mu_2(\tau)\left(1+\dot{\bar{\mathrm{z}}}^2(\tau)\right)\right], \qquad (4)$$

$$T = \frac{1}{2}\left(x_0+\bar{x}_0-y_0-\bar{y}_0\right), \quad \mu_1(\tau) = \frac{T}{2s}\dot{z}_0(\tau), \quad \mu_2(\tau) = \frac{T}{2\bar{s}}\dot{\bar{z}}_0(\tau),$$

and the no-backtracking time approximation [2,3]

$$\mu_1(\tau)>0, \quad \mu_2(\tau)>0 \qquad (5)$$

was used. Similarly to [2,3] we exploit in the valence quark sector (5) the approximation that the minimal surface S may be parametrized by the straight lines, connecting points $z_\mu(\tau)$ and $\bar{z}_\mu(\tau)$ with the same τ, i.e. the trajectories of a quark and antiquark are synchronized: $z_\mu = (\tau, \mathrm{z})$, $\bar{z}_\mu = (\tau, \bar{\mathrm{z}})$, $w_\mu(\tau,\beta) =$ $=\beta z_\mu(\tau)+(1-\beta)\bar{z}_\mu(\tau)$, $0\le\beta\le 1$.

Introducing auxiliary fields [2]

$$\nu(\tau,\beta) = T\sigma\frac{h_{22}}{\sqrt{h}}, \quad \eta(\tau,\beta) = \frac{1}{T}\frac{h_{12}}{h_{22}}$$

and making a rescaling

$$z_\mu\longrightarrow\sqrt{\frac{\sigma}{2\bar{\alpha}}}z_\mu, \quad \bar{z}_\mu\longrightarrow\sqrt{\frac{\sigma}{2\bar{\alpha}}}\bar{z}_\mu$$

one gets from the last exponent on the R.H.S. of Eq.(3) the following action of the string without quarks

$$A_{str.} = \int\limits_0^T d\tau\int\limits_0^1 d\beta\frac{\nu}{2}\left\{\dot{w}^2+\left(\left(\frac{\sigma}{\nu}\right)^2+\eta^2\right)r^2-2\eta(\dot{w}r)+\frac{\sigma T^2}{\alpha_0\bar{\alpha}^2}\frac{1}{h}\times\right.$$

$$\times\left[\ddot{w}^2r^2-(\ddot{w}r)^2+\dot{w}^2\dot{r}^2-(\dot{w}\dot{r})^2+2((\ddot{w}\dot{w})(\dot{r}r)-(\ddot{w}\dot{r})(\dot{w}r))+\right.$$

$$\left.\left.+\left(\left(\frac{\sigma}{\nu}\right)^2+\eta^2\right)\left(\dot{r}^2r^2-(\dot{r}r)^2\right)-2\eta\left((\ddot{w}\dot{r})r^2-(\ddot{w}r)(\dot{r}r)+(\dot{w}\dot{r})(\dot{r}r)-(\dot{w}r)\dot{r}^2\right)\right]\right\}, \qquad (6)$$

where a dot stands for $\partial/\partial\tau$, $r_\mu(\tau)=z_\mu(\tau)-\bar{z}_\mu(\tau)$ is the relative coordinate, and analogously to Ref.[1] we have assumed that the string world sheet is not much crumpled, so that h_{ab} is a smooth function.

Let us now introduce the centre of masses coordinate $R_\mu(\tau)=\zeta(\tau)z_\mu(\tau)+(1-\zeta(\tau))\bar{z}_\mu(\tau)$, where $\zeta(\tau)\equiv\zeta_1(\tau)+\frac{1}{\alpha_0}\zeta_2(\tau)$, $0\le\zeta(\tau)\le1$, should be determined from the requirement that $\dot{R}_\mu$ decouples from $\dot{r}_\mu$ [3]. Next, assuming that a meson as a whole moves with a constant speed (which is true for a free meson), i.e. $\ddot{R}=0$, and bringing together quark kinetic terms (4) and pure string action (6), we arrive at the following action of the QCD string with quarks

$$A=\int\limits_0^T d\tau\Bigg\{\frac{m_1^2}{2\mu_1}+\frac{m_2^2}{2\mu_2}+\frac{\mu_1}{2}+\frac{\mu_2}{2}+\frac{1}{2}\left(\mu_1+\mu_2+\int\limits_0^1 d\beta\nu\right)\dot{R}^2+$$

$$+\left(\mu_1(1-\zeta_1)-\mu_2\zeta_1+\int\limits_0^1 d\beta(\beta-\zeta_1)\nu\right)(\dot{R}\dot{r})-\int\limits_0^1 d\beta\nu\eta\,(\dot{R}r)+\int\limits_0^1 d\beta(\zeta_1-\beta)\eta\nu(\dot{r}r)+$$

$$+\frac{1}{2}\left(\mu_1(1-\zeta_1)^2+\mu_2\zeta_1^2+\int\limits_0^1 d\beta(\beta-\zeta_1)^2\nu\right)\dot{r}^2+\frac{1}{2}\int\limits_0^1 d\beta\left(\frac{\sigma^2}{\nu}+\eta^2\nu\right)r^2+$$

$$+\frac{1}{\alpha_0}\Bigg[\zeta_2(\mu_1(\zeta_1-1)+\mu_2\zeta_1)\dot{r}^2-\zeta_2(\mu_1+\mu_2)\,(\dot{R}\dot{r})+\int\limits_0^1 d\beta\nu\Bigg(\zeta_2(\zeta_1-\beta)\dot{r}^2-\zeta_2\,(\dot{R}\dot{r})+\zeta_2\eta(\dot{r}r)+$$

$$+\frac{1}{2}(\beta-\zeta_1)^2\,[\ddot{\mathbf{r}},\mathbf{r}]^2+\frac{1}{2}\dot{R}^2\dot{r}^2-\frac{1}{2}\left(\dot{R}\dot{r}\right)^2+(\beta-\zeta_1)\left((\ddot{r}\dot{R})\,(\dot{r}r)-(\ddot{r}\dot{r})\,(\dot{R}r)\right)+$$

$$+\frac{1}{2}\left(\left(\frac{\sigma}{\nu}\right)^2+\eta^2\right)[\dot{\mathbf{r}},\mathbf{r}]^2+\eta\Big((\beta-\zeta_1)\left((\ddot{r}r)(\dot{r}r)-(\ddot{r}\dot{r})r^2\right)+(\dot{R}r)\,\dot{r}^2-(\dot{R}\dot{r})\,(\dot{r}r)\Big)\Bigg)\Bigg]\Bigg\},\quad(7)$$

where we have performed a rescaling

$$z_\mu\longrightarrow\bar{\alpha}\sqrt{\frac{h}{\sigma T^2}}z_\mu,\quad \bar{z}_\mu\longrightarrow\bar{\alpha}\sqrt{\frac{h}{\sigma T^2}}\bar{z}_\mu,\quad \nu\longrightarrow\frac{\sigma T^2}{\bar{\alpha}^2h}\nu.$$

Integrating over η, one gets in the zeroth order in $1/\alpha_0$

$$\eta_{ext.}=\frac{(\dot{r}r)}{r^2}\left(\beta-\frac{\mu_1}{\mu_1+\mu_2}\right),$$

which together with the condition $\dot{R}\dot{r}=0$ yields

$$\zeta_2^{ext.}=\frac{(\dot{r}r)^2}{r^2}\frac{\frac{\mu_1}{\mu_1+\mu_2}\int\limits_0^1 d\beta\nu-\int\limits_0^1 d\beta\beta\nu}{\mu_1+\mu_2+\int\limits_0^1 d\beta\nu},$$

while $\zeta_1^{ext.}=[\mu_1+\int\limits_0^1 d\beta\beta\nu]/[\mu_1+\mu_2+\int\limits_0^1 d\beta\nu]$ was found in Ref.[3].

Finally, in order to obtain the desirable Hamiltonian, we shall perform the usual canonical transformation from $\dot{\mathbf{R}}$ to the total momentum $\mathbf{P}$ in the Minkowski space-time

$$\int D\mathbf{R}\exp\left[i\int L\left(\dot{\mathbf{R}},...\right)d\tau\right]=\int D\mathbf{R}D\mathbf{P}\exp\left[i\int\left(\mathbf{P}\dot{\mathbf{R}}-H\left(\mathbf{P},...\right)\right)d\tau\right],$$

where $H(\mathbf{P},...) = \mathbf{P}\dot{\mathbf{R}} - L(\dot{\mathbf{R}},...)$, and choose the meson rest frame as $\mathbf{P} = \partial L(\dot{\mathbf{R}},...)/\partial\dot{\mathbf{R}} = 0$. After performing the transformation from $\dot{\mathbf{r}}$ to $\mathbf{p}$ we get the following Hamiltonian

$$H = H^{(0)} + \frac{1}{\alpha_0} H^{(1)}. \tag{8}$$

Here

$$H^{(0)} = \frac{1}{2}\left[\frac{(\mathbf{p}_r{}^2 + m_1^2)}{\mu_1} + \frac{(\mathbf{p}_r{}^2 + m_2^2)}{\mu_2} + \mu_1 + \mu_2 + \sigma^2 \mathbf{r}^2 \int_0^1 \frac{d\beta}{\nu} + \nu_0 + \frac{\mathbf{L}^2}{\rho \mathbf{r}^2}\right] \tag{9}$$

with

$$\rho = \mu_1 + \nu_2 - \frac{(\mu_1 + \nu_1)^2}{\mu_1 + \mu_2 + \nu_0}, \quad \nu_i \equiv \int_0^1 d\beta \beta^i \nu, \quad \mathbf{p}_r{}^2 \equiv \frac{(\mathbf{p}\,\mathbf{r})^2}{\mathbf{r}^2}, \quad \mathbf{L} \equiv [\mathbf{r},\mathbf{p}]$$

is the Hamiltonian of the "minimal" Nambu-Goto string with quarks, which was derived and investigated in Ref.[3], while the new Hamiltonian $H^{(1)}$ has the form

$$H^{(1)} = \frac{a_1}{\rho^2}\mathbf{L}^2 + \frac{a_2}{\rho^2}\dot{\mathbf{L}}^2 + \frac{a_3}{2\tilde{\mu}^3}|\mathbf{r}|\,(\mathbf{p}_r{}^2)^{\frac{3}{2}} + \frac{a_4}{\tilde{\mu}^4}(\mathbf{p}_r{}^2)^2 + \frac{a_5}{2\tilde{\mu}\rho^2}\frac{\sqrt{\mathbf{p}_r{}^2\mathbf{L}^2}}{|\mathbf{r}|} + \frac{a_6}{2\tilde{\mu}^2\rho^2}\frac{\mathbf{p}_r{}^2\mathbf{L}^2}{\mathbf{r}^2}, \tag{10}$$

where $\tilde{\mu} = \frac{\mu_1\mu_2}{\mu_1+\mu_2}$, and the coefficients $a_k, k = 1,...,6$ read as follows

$$a_1 = \frac{\sigma^2}{2}\int_0^1 \frac{d\beta}{\nu}, \quad a_2 = \frac{1}{2}\left[\nu_2 + \frac{(\mu_1+\nu_1)(\nu_0(\mu_1-\nu_1) - 2\nu_1(\mu_1+\mu_2))}{(\mu_1+\mu_2+\nu_0)^2}\right], \quad a_3 = 3\frac{\dot{\tilde{\mu}}}{\tilde{\mu}}B - \dot{B},$$

$$a_4 = \frac{1}{2(\mu_1+\mu_2)(\mu_1+\mu_2+\nu_0)}\left[\frac{\nu_0(\mu_1\nu_0 - \nu_1(\mu_1+\mu_2))^2}{(\mu_1+\mu_2)(\mu_1+\mu_2+\nu_0)} - \nu_1(\mu_1+\mu_2)(\nu_1 - 2\mu_2) - \right.$$

$$\left. -\mu_1\nu_0(\mu_1 + 2\mu_2)\right],$$

$$a_5 = \frac{\dot{\tilde{\mu}}}{\tilde{\mu}}B - \dot{B},$$

$$a_6 = \nu_2 + \frac{\nu_1^2 + 2\mu_1\nu_0 - 2\mu_2\nu_1}{\mu_1+\mu_2+\nu_0} + \frac{1}{\mu_1+\mu_2}\times$$

$$\times\left[\frac{1}{\mu_1+\mu_2}\left(\frac{(\mu_1\nu_0 - \nu_1(\mu_1+\mu_2))^2(3\nu_0 + 2(\mu_1+\mu_2))}{(\mu_1+\mu_2+\nu_0)^2} + \right.\right.$$

$$\left.\left. + \mu_1(\mu_1\nu_0 - 2\nu_1(\mu_1+\mu_2))\right) - \frac{\mu_1^2\nu_0}{\mu_1+\mu_2+\nu_0}\right], \quad B \equiv \frac{\nu_1(\mu_1+\mu_2)(\nu_1 - 2\mu_2) + \mu_1\nu_0(\mu_1+2\mu_2)}{(\mu_1+\mu_2)(\mu_1+\mu_2+\nu_0)}.$$

During the derivation of $H^{(1)}$ we have chosen the origin at the centre of masses of the initial state, so that $\dot{\mathbf{R}}\dot{\mathbf{r}} \ll 1$, and the term

$$-\frac{1}{2\alpha_0}\int_0^T d\tau \nu_0 (\dot{\mathbf{R}}\dot{\mathbf{r}})^2$$

on the R.H.S. of Eq.(7) has been neglected.

Notice, that Hamiltonian (8)-(10) contains auxiliary fields μ_1, μ_2 and ν. In order to construct the operator Hamiltonian, acting upon wave functions, one should integrate over these fields (that implies the substitution of their extremal values, which could be obtained from the corresponding saddle point equations, into Eqs.(8)-(10)) and perform Weil ordering [11].

Let us now apply Hamiltonian (10) to the derivation of the rigid string correction to the Hamiltonian of the so-called relativistic quark model [9], i.e. consider the case when the orbital momentum is equal to zero. In what follows we shall put for simplicity the mass of a quark being equal to the mass of an antiquark $m_1 = m_2 \equiv m$. In order to get $H^{(1)}$, one should substitute the extremal values of the fields μ_1, μ_2 and ν of the zeroth order in $1/\alpha_0$, $\mu_1^{ext.} = \mu_2^{ext.} = \sqrt{\mathbf{p}^2 + m^2}$ and $\nu_{ext.} = \sigma |\mathbf{r}|$, into Eq.(10). The limit of large masses of a quark and antiquark means that $m \gg \sqrt{\sigma}$. In this case we obtain from Eq.(10) the rigid string Hamiltonian $H^{(1)} = -\frac{4\sigma|\mathbf{r}|}{m^4}\left(\mathbf{p}_r{}^2\right)^2$ and then from Eqs.(8) and (9) the following expression for the total Hamiltonian

$$H = 2m + \sigma|\mathbf{r}| + \frac{\mathbf{p}^2}{m} - \left(\frac{1}{4m^3} + \frac{4\sigma|\mathbf{r}|}{\alpha_0 m^4}\right)\left(\mathbf{p}^2\right)^2. \tag{11}$$

3. In this letter we have derived a correction to Hamiltonian (9) of the QCD string with spinless quarks, which was found in Ref.[3], arising due to the rigidity term in the gluodynamics string effective action [1]. This correction is given by formula (10). The Hamiltonian obtained contains corrections to the orbital momentum of the system and also several operators higher than of the second order in the momentum. The latter ones arise as a consequence of the fact that the rigid string theory is a theory with higher derivatives.

Making use of the obtained Hamiltonian we have derived a rigid string contribution to the Hamiltonian of the relativistic quark model in the case of equal large masses of a quark and antiquark, so that the total Hamiltonian is given by formula (11).

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