PROCEEDINGS OF SCIENCE

Hybrid charmonium

Yu. S. Kalashnikova
Institute of Theoretical and Experimental Physics, 117218, B. Cheremushkinskaya 25, Moscow, Russia
E-mail: yulia@itep.ru

A. V. Nefediev*
Institute of Theoretical and Experimental Physics, 117218, B. Cheremushkinskaya 25, Moscow, Russia
E-mail: nefediev@itep.ru

Lowest charmonium hybrids are considered in the framework of the QCD string model. All parameters of the model are fixed from the fit for the spectrum of conventional charmonia. Then masses, spin splittings, and relative decay rates into various S- and P-wave D-meson pairs are calculated for charmonium hybrids with a magnetic gluon. Results are compared with the lattice predictions and with the existing experimental data. A possible interpretation of the $Y(4260)$ as a hybrid meson is discussed and consequences of such an identification are outlined.

PACS: 12.39.-x, 13.25.Jx, 14.40.Gx

8th Conference Quark Confinement and the Hadron Spectrum
September 1-6 2008
Mainz, Germany

*Speaker.

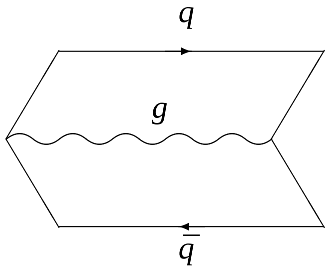

Figure 1: Wilson loop configuration corresponding to the propagation of the hybrid state.

QCD predicts the existence of hadronic states with an excited gluonic degree of freedom, hybrid mesons being the simplest such hadrons. In spite of many theoretical and experimental efforts, no states with an excited glue have been undoubtedly established so far. Thus two important questions should be raised, namely, whether such states indeed exist in Nature and, if the answer is in positive, how we can tell them from conventional quarkonia. Studies of the charmonium spectrum look very promising in this respect since the conventional charmonium can be well described in terms of quark models, so that disagreements between the experiment and the predictions of quark models for charmonium may signalise the presence of the gluonic degree of freedom in the experimentally observed state. For example, there exist strong arguments in favour of hybrid assignment for the recently observed $Y(4260)$ state [1]. It is seen in the initial state radiation process $e^+e^- \to \gamma\pi^+\pi^- J/\psi$ and is therefore a genuine vector state. In the meantime, its e^+e^- width is too small for a conventional $c\bar{c}$ vector, and there is no visible decay into $D\bar{D}$ pairs, in spite of the large phase space available. It is the latter feature that has prompted the hybrid interpretation of the $Y(4260)$[2], as the selection rule is established — see, for example, [3] — which forbids the decay of the vector hybrid into a $D^{(*)}\bar{D}^{(*)}$ final state.

Competing models for the $Y(4260)$ exist. One is the diquark–antidiquark model [4]. On the other hand, the $Y(4260)$ is not far from the $D\bar{D}_1$ threshold, where D_1 is a P–wave 1^+ charmed meson, so the $Y(4260)$ state could be associated with the opening of a new S–wave $D\bar{D}_1$ threshold [5]. In this regard it is important to assess the consequences of the hybrid assignment for the Y.

In this work, we study the predictions of the QCD string model [6] based on the Vacuum Correlators Method (see [7] for a review of the method) for the lowest charmonium hybrids and compare these predictions with the results of lattice simulations as well as with the recent experimental data [8]. In the framework of the QCD string model, hybrids can be considered as bound states of a quark–antiquark pair and a gluon [9]. In Fig. 1 the Wilson loop is depicted which describes the propagation of the hybrid. Such a picture allows one to make a number of predictions for the hybrids. First of all, the presence of an additional degree of freedom — of the gluon — makes it possible to obtain a set of states with the quantum numbers inaccessible for conventional mesons. For example, for the magnetic gluon ($l_g = j$), the quantum numbers of the hybrids read:

$$P = (-1)^{l_{q\bar{q}}+j}, \quad C = (-1)^{l_{q\bar{q}}+s_{q\bar{q}}+1}, \tag{1}$$

where $l_{q\bar{q}}$ and $s_{q\bar{q}}$, are the total quark-antiquark angular momentum and spin, while j is the total momentum of the gluon. In this scheme exotic quantum numbers are present, like 1^{-+}, which are not possible for plain $q\bar{q}$ states. On the other hand, the presence of the gluon hardens leptonic

Parameter	m, GeV	σ, GeV^2	α_s	C, MeV
Value	1.48	0.16	0.55	-28

Table 1: The set of parameters used for the numerical evaluation.

decays of the hybrids — the corresponding amplitude appears suppressed by extra powers of the strong and electromagnetic coupling constants. This property is consistent with the experimentally observed situation. As will be seen below, the selection rule which forbids decays of hybrids into two S-wave mesons can be easily obtained in the given scheme as well.

Let us briefly introduce the necessary essentials of the QCD string formalism. According to this method, any hadronic state can be build from an appropriate number of quarks, antiquarks, and gluons (also string junctions in case of baryons) connected by extended objects — the QCD strings. Vibrations of the string are described with the help of the gluons attached to the string, so that the hybrid meson can be viewed as the first excitation over the conventional meson caused by the string vibration, which is separated from the ground state by an energy gap of order 1 GeV. Every segment of the string, which can be approximated by a straight-line profile, gives rise to the confining interaction and to the nonperturbative spin-orbital interaction. Pair-wise Coulomb interactions between colour constituents bring about extra spin-dependent terms, such as the non-perturbative spin-orbital interactions, the hyperfine interactions, and the tensor forces. In particular, one has the following Hamiltonian of the hybrid:

$$H = H_0 + V_{\rm str} + V_{\rm SD} + C. \tag{2}$$

Here H_0 incorporates kinetic energies of the particles (with current masses involved), the linear confinement, and the Coulomb interactions,

$$H_0 = \frac{\mu_q+\mu_{\bar q}+\mu_g}{2} + \frac{m^2+p_q^2}{2\mu_q} + \frac{m^2+p_{\bar q}^2}{2\mu_{\bar q}} + \frac{p_g^2}{2\mu_g} + \sigma|\vec r_q-\vec r_g| + \sigma|\vec r_{\bar q}-\vec r_g| + V_{\rm Coul}, \tag{3}$$

$$V_{\rm Coul} = -\frac{3\alpha_s}{2|\vec r_q-\vec r_g|} - \frac{3\alpha_s}{2|\vec r_{\bar q}-\vec r_g|} + \frac{\alpha_s}{6|\vec r_q-\vec r_{\bar q}|}. \tag{4}$$

The coefficients in (4) correspond to the colour content of the $q\bar q g$ system [10]. The string correction $V_{\rm str}$ describes the effect of the proper inertia of the QCD string (see [6] for the details). The derivation of the spin–dependent potential $V_{\rm SD}$ can be found in [11], with the result:

$$V_{\rm SD} = V_{\rm LS}^{(q\bar q)} + V_{\rm LS}^{(g)} + V_{\rm SS} + V_{\rm ST}^{(q\bar q)} + V_{\rm ST}^{(g)}, \tag{5}$$

where the subscript LS stands for the spin–orbit interaction, SS — for the hyperfine interaction, ST — for the spin–tensor. Finally, the constant C in (2) stands for the selfenergy correction which can be evaluated in a selfconsistent manner in the framework of the VCM [12].

The Hamiltonian (2) is written with the help of the einbein fields μ_q, $\mu_{\bar q}$, and μ_g [13]. Extrema in all einbeins are understood. If such extrema are taken in the Hamiltonian (2), the standard relativistic kinetic energies are restored. It is convenient however to treat the einbeins as variational parameters and to eliminate them in the spectrum. For charmonium $\mu_q = \mu_{\bar q} = \mu$.

J^{PC}	0^{-+}	1^{-+}	1^{--}	2^{-+}
Mass	4.252	4.320	4.397	4.457

Table 2: Masses of charmonium hybrids, in GeV.

As we are interested in hybrids with a magnetic gluon, we use our trial w.f. in the form:

$$|1^{--}\rangle_m = \Phi(r,\rho)S_0(q\bar{q})\sum_{\nu_1\nu_2} C^{1m}_{1\nu_1 1\nu_2}\rho Y_{1\nu_1}(\hat{\rho})S_{1\nu_2}(g), \tag{6}$$

for the vector hybrid, with the quark–antiquark pair in the spin–singlet state $S_0(q\bar{q})$. In addition, for the spin–triplet quark–antiquark state a set of three hybrid siblings appear, with the w.f.'s:

$$|J^{-+}\rangle_m = \Phi(r,\rho)\sum_{\mu_1\mu_2} C^{Jm}_{1\mu_1 1\mu_2}S_{1\mu_1}(q\bar{q})\sum_{\nu_1\nu_2} C^{1\mu_2}_{1\nu_1 1\nu_2}\rho Y_{1\nu_1}(\hat{\rho})S_{1\nu_2}(g). \tag{7}$$

Here $S_{1\nu}(g)$ is the spin w.f. of the gluon, and $S_{1\nu}(q\bar{q})$ is the triplet spin w.f.'s of the $q\bar{q}$ pair. The "radial" w.f. $\Phi(r,\rho)$ depends on its arguments in the form of the hyperspherical radius R (see [14] for details of the hyperspherical harmonics) and is chosen in the Gaussian form,

$$\Phi(r,\rho) = \exp\left(-\frac{1}{2}\beta^2 MR^2\right), \quad R^2 = \frac{\mu_{12}}{M}r^2 + \frac{\mu_{12,3}}{M}\rho^2, \quad M = 2\mu + \mu_g, \tag{8}$$

with β being a variational parameter. Further details of calculations can be found in [8]. The set of parameters used in numerical calculations is given in Table 1. The derivation of the selfenergy correction C for the charmonium can be found in [12]. It takes the same value for the charmonium hybrid since the quark content of both states is identical. The set of parameters from Table 1 allows one to reproduce the spectrum of known S- and P-wave charmonia with a high accuracy [8]. Our theoretical predictions for the spectrum of hybrids are listed in Table 2. Notice that it follows from the explicit form of the hybrid w.f.'s (6) and (7) that decays into two S-wave D-mesons are forbidden, as was discussed before. In addition one can establish a set of spin–recoupling coefficients for the hybrid decays into pairs of S- and P-wave D-mesons — they are given in Table 3.

Notice that the predicted hybrid masses appears in good agreement with the results of lattice calculations [15]. Since a variational procedure was used in this work, the predictions given in Table 2 overestimate slightly the actual values of the hybrids masses. Besides that, hadronic shifts were not taken into account, which are also known to decrease the total mass of the state due to its coupling to the open channels. This makes the theoretical prediction quite close to the experimentally observed mass of 4260 MeV. Finally, the peculiar properties of the experimentally observed charmonium $Y(4260)$ can be explained naturally in the framework of the QCD string model. We therefore conclude that our predictions for the lowest charmonium hybrids are in good agreement with the lattice results and support identification of the state $Y(4260)$ as the lowest charmonium hybrid. If this is indeed the case, three sibling hybrid states, including the exotic one, should reside in the vicinity, so further experimental investigation, including establishing decay modes of the $Y(4260)$, is strongly needed in order to disclose its nature.

	$\bar{D}D_0$	$\bar{D}^*D_0$	$\bar{D}D_1[^1P_1]$	$\bar{D}^*D_1[^1P_1]$	$\bar{D}D_1[^3P_1]$	$\bar{D}^*D_1[^3P_1]$	$\bar{D}D_2$	$\bar{D}^*D_2$
1^{--}		$1/\sqrt{6}$		$-1/2$	$1/2$	$\sqrt{2}/4$		$-\sqrt{30}/12$
0^{-+}	$-1/\sqrt{2}$			$1/\sqrt{2}$				
1^{-+}		$-1/\sqrt{3}$	$-1/2$	$\sqrt{2}/4$	$\sqrt{2}/4$	$1/4$		$-\sqrt{15}/12$
2^{-+}				$-\sqrt{2}/4$		$3/4$	$\sqrt{2}/4$	$\sqrt{3}/4$

Table 3: Spin–recoupling coefficients for the hybrid states. Here $D^{(*)}$ is an S–wave $D^{(*)}$-meson and D_J is a P–wave D–meson with the total momentum J. A proper charge conjugation is implied.

Acknowledgments

This research was supported by the “Rosatom" State Corporation of Russian Federation, by the grants RFFI-05-02-04012-NNIOa, DFG-436 RUS 113/820/0-1(R), PTDC/FIS/70843/2006-Fisica, NSh-4961.2008.2, and by the non-profit “Dynasty" foundation and ICFPM.

References

[1] B. Aubert *et al* [BaBar Collaboration], *Phys. Rev. Lett.* **95** (2005) 142001.

[2] S.-L. Zhu, *Phys. Lett. B* **625** (2005) 212.

[3] A. Le Yaouanc, L. Oliver, O. Pene, J.-C. Raynal, and S. Ono, *Z. Phys. C* **28** (1985) 309; F. Iddir, S. Safir, and O. Pene, *Phys. Lett. B* **433** (1998) 125; Yu. S. Kalashnikova, *Z. Phys. C* **62** (1994) 323. E. Kou and O. Pene, *Phys. Lett. B* **631** (2005) 164; N. Isgur, R. Kokoski, and J. Paton, *Phys. Rev. Lett.* **54** (1985) 869; F. E. Close and P. R. Page, *Nucl. Phys. B* **443** (1995) 233.

[4] L. Maiani, V. Riquer, F. Piccinini, and A. D. Polosa, *Phys. Rev. D* **72** (2005) 031502(R); D. Ebert, R. N. Faustov, V. O. Galkin, arXiv:0808.3912[hep-ph].

[5] J. L. Rosner, *Phys. Rev. D* **74** (2006) 076006.

[6] A. Yu. Dubin, A. B. Kaidalov, and Yu. A. Simonov, *Phys. Lett. B* **323** (1994) 41.

[7] A. Di Giacomo, H. G. Dosch, V. I. Shevchenko, and Yu. A. Simonov, *Phys. Rep.* **372** (2002) 319.

[8] Yu. S. Kalashnikova and A. V. Nefediev, *Phys. Rev. D* **77** (2008) 054025.

[9] Yu. A. Simonov, *Nucl. Phys. B (Proc Suppl)* **23** (1991) 283; Yu. S. Kalashnikova and Yu. B. Yufryakov, *Phys. Lett. B* **359** (1995) 175; Yu. A. Simonov, *Phys. At. Nucl.* **68** (2005) 1294; Yu. S. Kalashnikova and D. S. Kuzmenko, *Phys. At. Nucl.* **66** (2003) 955.

[10] D. Horn and J. Mandula, *Phys. Rev. D* **17** (1978) 898.

[11] A. M. Badalian and Yu. A. Simonov, *Phys. At. Nucl.* **59** (1996) 2164; Yu. A. Simonov, in proceedings of the *XVII International School of Physics “QCD: Perturbative or Nonperturbative,"* Lisbon, 1999, ed. by L. S. Ferreira, P. Nogueira, and J. I. Silva-Marcos (World Scientific 2000), p. 60.

[12] Yu. A. Simonov, *Phys. Lett. B* **515** (2001) 137.

[13] L. Brink, P. Di Vecchia, and P. Howe, *Nucl. Phys. B* **118** (1977) 76.

[14] Yu. A. Simonov, *Phys. Lett. B* **228** (1989) 413; M. Fabre de la Ripelle and Yu. A. Simonov, *Ann. Phys. (N.Y.)* **212** (1991) 235.

[15] C. Michael, arXiv:hep-ph/0308293; J. J. Dudek, R. G. Edwards, N. Mathur, and D.G. Richards *Phys. Rev. D* **77** (2008) 034501.