Perspective Study of Charmonium and Exotics above $D\bar{D}$ Threshold

M. Yu. Barabanov, A. S. Vodopyanov

Joint Institute for Nuclear Research, Joliot-Curie 6, Dubna, Moscow region Russia 141980

The spectroscopy of exotic states with hidden charm is discussed. Together with charmonium it is a good testing tool for theories of strong interactions including QCD in both perturbative and non-perturbative regime, lattice QCD, potential models and phenomenological models. An elaborated analysis of exotics spectrum is given, and attempts to interpret recent experimental data in the above $D\bar{D}$ threshold region are considered. Experimental data from different collaborations (BES, BaBar, Belle, LHCb) are analyzed with special attention given to new states with hidden charm which were discovered recently. Some of these states can be interpreted as higher-lying charmonium states and tetraquarks with hidden charm. It has been shown that charge/neutral tetraquarks must have their neutral/charge partners with mass values differ by few MeV. This hypothesis coincides with that proposed by Maiani and Polosa. But much more data on different decay modes are needed before firmer conclusions can be made. These data can be derived directly from the experiments using the high quality antiproton beam with momentum up to 15 GeV/c and proton-proton collisions with momentum up to 26 GeV/c.

1 Introduction

The study of strong interactions and hadron matter in the process of antiproton-proton annihilation and proton-proton collisions seems to be a challenge nowadays. One of the main goals of contemporary physics is to search for new exotic forms of matter, which must manifest in the existence of charmed hybrids and multiquark states such as meson molecules and tetraquarks [1, 2]. The researches of spectrum of charmed hybrids $c\bar{c}g$ and tetraquarks with hidden charm ($cq\bar{c}\bar{q}'$, and q and $q' = u$, d, s) together with the charmonioum spectrum are promising to understand the dynamics of quark interactions at small distances. It is a good testing tool for the theories of strong interactions: QCD in both perturbative and non-perturbative regimes, QCD inspired potential models, phenomenological models, non-relativistic QCD and LQCD.

Charmed hybrids $c\bar{c}g$ represent themselves as the states with an excited gluonic degree of freedom. These states are described by different models and calculation schemes (LQCD, bag model, flux tube model) [1, 2]. All model predictions and calculations agree that the mass of the lowest-lying charmonium hybrids is between 3.9 and 4.6 GeV/c^2 and that the state with $J^{PC} = 1^{-+}$ has the lowest mass. Until now, discussions have been focused only around the lowest-lying charmonium hybrids. Four of these states $J^{PC} = 2^{-+}$, 1^{-+}, 1^{--}, 0^{-+} correspond to a $c\bar{c}$ pair with $J^{PC} = 0^{-+}$ or 1^{--}, coupled to a gluon in the lightest mode with $J^{PC} = 1^{+-}$. The other four states $J^{PC} = 2^{+-}$, 1^{+-}, 1^{++}, 0^{+-} with the gluon mode

$J^{PC} = 1^{-+}$ are, probably, a bit heavier. The expected mass splitting between the states 1^{-+} and 0^{+-} is about 150 - 250 MeV. Three of these eight charmonium hybrids have spin-exotic quantum numbers 1^{-+}, 0^{+-}, 2^{+-}, so mixing effects with nearby $c\bar{c}$ states are excluded for them thus making their experimental identification especially easy. The next possible hybrid states with quantum numbers 2^{++}, 2^{+-}, 1^{++}, 1^{+-}, 0^{+-}, 0^{++} correspond to $c\bar{c}$ pairs with quantum numbers $J^{PC} = 1^{+-}$ or $J^{PC} = (0,1,2)^{++}$ coupled to a gluon in the lightest mode with $J^{PC} = 1^{+-}$. The states with quantum numbers 2^{--}, 2^{-+}, 1^{--}, 1^{-+}, 0^{-+}, 0^{--} correspond to pair $c\bar{c}$ with quantum numbers $J^{PC} = 1^{+-}$ or $J^{PC} = (0,1,2)^{++}$ coupled to a gluon mode with $J^{PC} = 1^{-+}$. One can find a possibility of the existence of hybrid state with exotic quantum numbers $J^{PC} = 0^{--}$. The most interesting and promising decay channels of charmed hybrids are as follows: $\bar{p}p \to \tilde{\eta}_{c0,1,2}(0^{-+}, 1^{-+}, 2^{-+})\eta \to \chi_{c0,1,2}(\eta, \pi\pi; \ldots)$; $\bar{p}p \to \tilde{h}_{c0,1,2}(0^{+-}, 1^{+-}, 2^{+-})\eta \to \chi_{c0,1,2}(\eta, \pi\pi; \ldots)$; $\bar{p}p \to \tilde{\Psi}(1^{--}, 2^{--}) \to J/\psi(\eta, \omega, \pi\pi; \ldots)$; $\bar{p}p \to \tilde{\eta}_{c0,1,2}, \tilde{h}_{c0,1,2}, \tilde{\chi}_{c1}(0^{-+}, 1^{-+}, 2^{-+}, 0^{+-}, 1^{+-}, 2^{+-}, 1^{++}, 2^{++})\eta \to D\bar{D}_J^*\eta$.

Two generic types of multiquark states have been described in the literature [3, 4, 5]. The first one, the molecular state, is comprised of two charmed mesons bound together to form a molecule. These states are by nature loosely bound. Molecular states bound through two mechanisms: quark/colour exchange interactions at short distances and pion exchange at a large distance. Since the mesons inside the molecule are weakly bound, they tend to decay as if they are free. The second type is a tightly bound four-quark state, so called tetraquark that is predicted to have properties that are different from those of a molecular state. In the model of Maiani [4, 5], for example, the tetraquark is described as a diquark-diantiquark structure in which the quarks group into the colour-triplet scalar and vector clusters and the interactions are dominated by a simple spin-spin interaction. Here, strong decays are expected to proceed via rearrangement processes followed by dissociation that gives rise, for example, to such decays as: $p\bar{p} \to X \to J/\psi \rho \to J/\psi \pi\pi$; $p\bar{p} \to X \to J/\psi \omega \to J/\psi \pi\pi\pi$; $p\bar{p} \to X \to \chi_{cJ}\pi$; $p\bar{p} \to X \to D\bar{D}^* \to D\bar{D}\gamma$; $p\bar{p} \to X \to D\bar{D}^* \to D\bar{D}\eta$. A prediction that distinguishes tetraquarks containing a $c\bar{c}$ pair from conventional charmonia is possible existence of multiplets which include members with non-zero charge $cu\bar{c}\bar{d}$, strangeness $cd\bar{c}\bar{s}$, or both $cu\bar{c}\bar{s}$.

2 Calculation of exotics spectrum

For this purpose we have fulfilled the elaborated analysis of the spectrum of charmed hybrids and tetraquarks with the hidden charm in the mass region above $D\bar{D}$ threshold. The analysis of spectrum of charmonium [6, 7] was carried out earlier. Different decay modes of charmed hybrids and tetraquarks such as decays into charmonium and light mesons and decays into $D\bar{D}_J^*$ and $D\bar{D}^*$ pairs, were, in particular, analyzed. A special attention was given to the new states with the hidden charm discovered recently [2, 3, 4, 5]. The experimental data from different collaborations like Belle, BaBar, LHCb, BES were carefully analyzed. Using the combined approach based on the quarkonium potential model and confinement model [8, 9], more than twenty charmed hybrids are expected to exist in the discussed mass region (see Figs. 1, 2).

Charmed hybrids with exotic quantum numbers are marked with dark colour and charmed hybrids with nonexotic quantum numbers – with light colour. The results of calculations for hybrids are in good agreement with the well accepted picture that the quartet 1^{--}, $(0,1,2)^{-+}$ is lower in mass than 1^{++}, $(0,1,2)^{+-}$. The mass splitting between the states 1^{-+} and 0^{+-} is about 200 MeV/c^2. More than twenty tetraquarks with hidden charm (see Fig. 3) are expected to exist in the mass region above $D\bar{D}$ threshold.
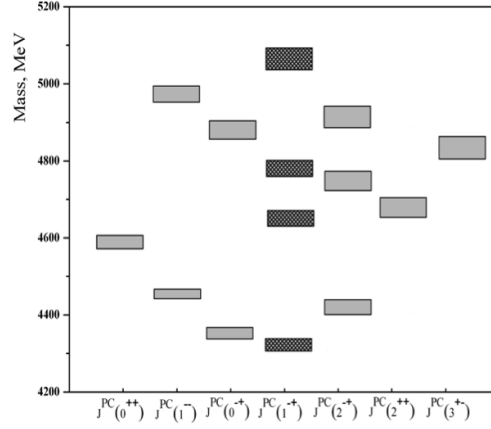
Figure 1: The spectrum of charmed hybrids with quantum numbers $J^{PC} = 3^{+-}$, 2^{++}, 2^{-+}, 1^{-+}, 1^{--}, 0^{-+}, 0^{++}.

The black-white boxes correspond to the recently revealed XYZ states with the hidden charm that may be interpreted as tetraquarks. White boxes correspond to the tetraquark states which have not been found yet. But a possibility of existence of these states is predicted in the framework of the combined approach. It has been shown that charge/neutral tetraquarks with hidden charm must have their neutral/charged partners with mass values which differ by few MeV. This assumption coincides with that proposed earlier by Maiani and Polosa [10] and can shed light on the nature of neutral $X(3872)$, $X(4350)$ and charged $Z_c(3885)^{\pm}$, $Z_c(3900)^{\pm}$, $Z_c(4020)^{\pm}$, $Z_c(4025)^{\pm}$, $Z_c(4200)^{\pm}$, $Z_c(4050)^{\pm}$, $Z_c(4250)^{\pm}$, $Z_c(4430)^{\pm}$ states. The quantum numbers J^{PC} of the $X(3872)$ meson have been recently determined by LHCb [11]. One can find that $X(3872)$ may be interpreted as tetraquark state with $J^{PC} = 1^{++}$, and $X(4350)$ as the tetraquark state with $J^{PC} = 2^{++}$. New state $Z_c(3900)^{\pm}$ observed by BES [12] together with $Z_c(4050)^{\pm}$, $Z_c(4250)^{\pm}$, $Z_c(4430)^{\pm}$ states may be interpreted as charge tetraquarks with $J^{PC} = 1^{+}$. New state $Z_c(4020)^{\pm}$ observed by BES [13] may be interpreted as charge tetraquark with $J^{PC} = 1^{+}$. The proposed approach doesn't distinguish the states $Z_c(3900)^{\pm}$ and $Z_c(3885)^{\pm}$ as well $Z_c(4025)^{\pm}$ and $Z_c(4020)^{\pm}$ states. The values of their masses and widths coincide in the framework of the combined approach. Two states (one charge and one neutral) with $J^{PC} = 1^{++}$ are expected to exist in the mass range of 4200 - 4300 MeV. The new charged state $Z_c(4250)^{\pm}$ observed by Belle may be a good candidate for the one of them.

To confirm that the predicted states actually exist and can be found experimentally, their widths and branching ratios were calculated [7, 9]. The feature of the considered states is their narrowness compared with light unflavored mesons, baryons and hybrids. The states we find in this model have small widths; their values are of the order of several tens of MeV. This fact facilitates experimental searches. The values of the calculated widths coincide (within the experimental error) with the experimentally determined values for the XYZ particles; the correspondence of the mass values has been discussed above. This fact strongly suggests that some of the XYZ particles may be interpreted as higher-lying charmonium states [6, 7] and tetraquarks as it can be verified by the experiments with antiproton beams with momentum up to 15 GeV/c and proton-proton collisions with momentum up to 26 GeV/c. The values of

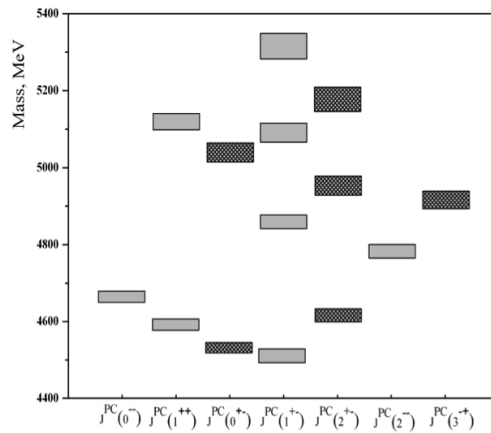Figure 2: The spectrum of charmed hybrids with quantum numbers $J^{PC} = 3^{-+}$, 2^{--}, 2^{+-}, 1^{+-}, 1^{++}, 0^{+-}, 0^{--}.

branching ratios in the considered decay channels of charmonium and exotics are of the order of $\beta \approx 10^{-1} - 10^{-2}$ dependent of their decay mode. From this one can conclude that the branching ratios are significant and searches for charmonium and exotics, and studies of the main characteristics of their spectrum seem to be promising.

3 Conclusion

The prospects for future exotics research are related with the results obtained below:

A combined approach has been employed to study charmonium and exotics on the basis of the quarkonium potential model and a confinement model that uses a three-dimensional sphere embedded into the four-dimensional Euclidian space of the decay products.
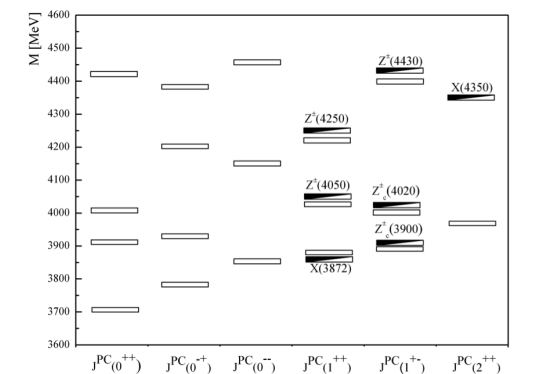

Figure 3: The spectrum of tetraquarks with hidden charm.

The most interesting and promising decay channels of charmed hybrids and tetraquarks with the hidden charm have been analyzed. Many new states above $D\bar{D}$ threshold are expected to exist in the framework of this model.

The recently discovered states with the hidden charm above the $D\bar{D}$ threshold (XYZ particles) have been analyzed. Ten of these states can be interpreted as higher-lying tetraquark states with hidden charm. The necessity of further studies of the XYZ particles and improved measurements of their main characteristics has been demonstrated.

References

[1] W. Erni *et al.*, arXiv:0903.3905v1 [hep-ex] (2009).

[2] N. Brambilla *et al.*, Eur. Phys. J. C 71: 1534, 1 (2011).

[3] J. Beringer *et al.*, Review of Particle Physics, Phys. Rev. 86 (2012).

[4] S. Godfrey and S. Olsen, Ann. Rev. Nucl. Part. Sci. 58, 51 (2008).

[5] S. Olsen, arXiv : 0909.2713v1 [hep-ex] (2009).

[6] M.Yu. Barabanov, A.S. Vodopyanov, Fizika Elementarnyh Chastits Atomnogo Yadra Pisma, 8, N.10, 63 (2011) / Phys. Part. Nucl. Lett. N.10, 1069 (2011).

[7] M.Yu. Barabanov, A.S. Vodopyanov, S. L. Olsen, Yadernaya Fizica, V.77, N.1, 1 (2014) / Phys. At. Nucl., V.77, N.1,1 26 (2014).

[8] M.Yu. Barabanov et al., Russ. Phys. J., 50, 1243 (2007).

[9] M.Yu. Barabanov et al., Hadronic J., 32, N.2, 159 (2009).

[10] N.V. Drenska, R. Fassini, A.D. Polosa, arXiv: 0902.2803 [hep-ph] (2009).

[11] R. Aaij et al., arXiv: 1302.6269v1 [hep-ex] (2013).

[12] M. Ablikim *et al.*, arXiv: 1303.5949v1 [hep-ex] (2013).

[13] M. Ablikim *et al.*, arXiv: 1308.2760v1 [hep-ex] (2013).