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New perspectives for study charmonium and exotics above $D\overline{D}$ threshold

M.Yu. Barabanov[1]
Joint Institute for Nuclear Research
Joliot-Curie 6 Dubna Moscow region Russia
E-mail: barabanov@jinr.ru

A.S. Vodopyanov
Joint Institute for Nuclear Research
Joliot-Curie 6 Dubna Moscow region Russia
E-mail: alexander.vodopyanov@cern.ch

The spectroscopy of charmonium and exotics is discussed. It is a good testing tool for the theories of strong interactions, including: QCD in both the perturbative and non-perturbative regimes, LQCD, potential models and phenomenological models. For this purpose an elaborated analysis of the charmonium, charmed hybrids and tetraqurks spectra is given, and attempts to interpret recent experimental data in the above $D\overline{D}$ threshold region are considered. Experiments using antiproton beams take advantage of the intensive production of particle-antiparticle pairs in antiproton-proton annihilations. Experimental data from different collaborations are analyzed with special attention given to new states with hidden charm that were discovered recently. Some of these states can be interpreted as higher-lying charmonium states and tetraquarks with a hidden charm. 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 a high quality antiproton beam with momenta up to 15 GeV/*c*.

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1.Introduction

The study of strong interactions and hadronic matter in the process of antiproton-proton annihilation seems to be a challenge nowadays. The research of charmonium and exotic states such as charmed hybrid and tetraquark spectra, and their main characteristics: mass, width and branching ratios in experiments using antiproton beam with momentum ranging from 1 to 15 GeV/c at FAIR, is one of the main components of PANDA physical program. The reactions of antiprotons impinging on proton or nuclear targets embedded in the High Energy Storage Ring, will be studied in these experiments [1].

In the last few years we are witnessing the discovery of a number of new narrow hadronic resonances with charm which do not match standard quark-antiquark interpretation, thereby named exotic hadrons [2, 3]. This has called for alternative interpretations of their inner structure. One of the possible explanations is that these particles are loosely bound molecules of open charm mesons. Another is that new aggregation patterns of quarks in matter are possible. Most of these states were observed above the $D\bar{D}$ threshold in some definite channel. New particles were produced from *B*-meson decays and in electron-positron or two-photon collisions. Many recently discovered states above the $D\bar{D}$ threshold expect their verification and explanation. Now their interpretation is far from being obvious [2, 3, 4].

Charmed hybrids represent themselves as the states with an excited gluonic degree of freedom. These states are described by different models and calculation schemes [1, 2, 4]. 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 MeV - 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 $c\bar{c}$ pair 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 $c\bar{c}$ pair 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: $\bar{p}p \to \tilde{\eta}_{c0,1,2}\ (0^{-+}, 1^{-+}, 2^{-+})\ \eta \to \chi_{c0,1,2}(\eta, \pi\pi;\ldots)$; $\bar{p}p \to \tilde{h}_{c0,1,2}\ (0^{+-}, 1^{+-}, 2^{+-})\ \eta \to \chi_{c0,1,2}(\eta, \pi\pi;\ldots)$; $\bar{p}p \to \tilde{\Psi}\,(1^{--}, 2^{--}) \to J/\Psi\,(\eta, \omega, \pi\pi,\ldots)$; $\bar{p}p \to \tilde{\eta}_{c0,1,2}, \tilde{h}_{c0,1,2}, \tilde{\chi}_{c1}\ (0^{-+}, 1^{-+}, 2^{-+}, 0^{+-}, 1^{+-}, 2^{+-}, 1^{++}, 2^{++})\ \eta \to D\bar{D}_J^{*}\eta$.

An early quark model prediction was the existence of multiquark states, specifically bound meson antimeson molecular states. Two generic types of multiquark states have been described in the literature [4]. The first, loosely bound molecular state, is comprised of two charmed mesons bound together to form a molecule. The second type, tightly bound tetraquark that is predicted to have properties that are distinct from those of a molecular state. In the model of Maiani [4], for example, the tetraquark is described as a diquark-diantiquark structure in which the quarks group into 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: $\bar{p}p \rightarrow X \rightarrow J/\Psi\,\rho \rightarrow J/\Psi\,\pi\pi$; $\bar{p}p \rightarrow X \rightarrow J/\Psi\,\omega \rightarrow J/\Psi\,\pi\pi\pi$, $\bar{p}p \rightarrow X \rightarrow \chi_{cJ}\,\pi$; $\bar{p}p \rightarrow X \rightarrow D\bar{D}^* \rightarrow D\bar{D}\,\gamma$; $\bar{p}p \rightarrow X \rightarrow D\bar{D}^* \rightarrow D\bar{D}\,\eta$. A prediction that distinguishes tetraquark states 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 charmonium and exotics spectrum

For this purpose we have fulfilled the elaborated analysis of the spectrum of tetraquarks with the hidden charm. The analysis of spectrum of charmonium states [5, 6] and charmed hybrids [7] was carried out earlier. Different decay modes of tetraquarks such as decays into light mesons and decays into $D\bar{D}^*$ pair, were, in particular, analyzed. A special attention was given to the new states with the hidden charm discovered recently (*XYZ*-particles) [2, 3, 4]. The experimental data from different collaborations like Belle, BaBar, BES, CDF were carefully analyzed. Using the combined approach based on the quarkonium potential model and confinement model on a three-dimensional sphere embedded into the four-dimensional Euclidian space [8, 9], more than twenty tetraquarks were predicted in the mass region above $D\bar{D}$ threshold (see Fig. 1). 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 must have their neutral/charged partners with mass values which differ by few MeV. This assumption can shed light on the nature of neutral $X(3872)$, $X(4350)$ and charged $Z(4050)^{\pm}$, $Z(4250)^{\pm}$, $Z(4430)^{\pm}$ states. The quantum numbers J^{PC} of the $X(3872)$ meson have been recently determined by LHCb [10]. One can find that $X(3872)$ may be interpreted as tetraquark state with $J^{PC} = 1^{++}$ and the new state $Z_c(3900)^{\pm}$ observed by BES [11], as its charged partner. The new state $Z_c(4025)^{\pm}$ observed by BES [12] may be interpreted as tetraquark state with $J^{PC} = 0^{++}$. The state $Z(4430)^{\pm}$ may be interpreted as charged tetraquark. The recently observed states $Z(4050)^{\pm}$ and $Z(4250)^{\pm}$ may be also interpreted as charged tetraquarks. Probably, $Z(4250)^{\pm}$ and $Z(4430)^{\pm}$ may be considered as radial excited states of $Z(4050)^{\pm}$. The new state $X(4350)$ may be interpreted as the tetraquark state with quantum numbers $J^{PC} = 2^{++}$. Two charged states $Z(3750)^{\pm}$ and $Z(3880)^{\pm}$ with $J^{PC} = 1^{+-}$ are expected to exist. This hypothesis coincides with that proposed by Maiani and Polosa.

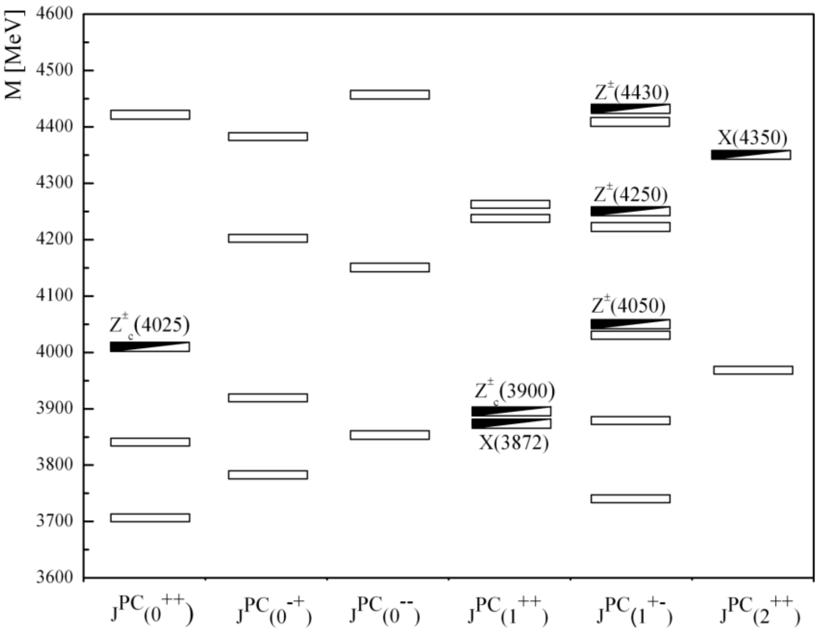

Figure 1. The spectrum of tetraquarks with hidden charm.

To confirm that the predicted states actually exist and can be found experimentally, their widths and branching ratios were calculated. 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 [5, 6] and tetraqurks. The values of 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 channel. 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 for the PANDA experiment at FAIR.

3.Conclusion

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

● Several promising decay channels of the charmed hybrids like decays into charmonium and light mesons in the final state and decays into $D\overline{D}_J^*$-pair were, in particular, considered. More than twenty charmed hybrids with exotic and nonexotic quantum numbers above $D\overline{D}$-threshold are expected to exist in the framework of the combined approach.

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● The most interesting and promising decay channels of tetraquarks like decays into charmonium and light mesons in the final state and decays into $D\bar{D}^*$-pair have been analyzed. More than twenty tetraquarks with the hidden charm in the mass region above $D\bar{D}$-threshold are expected to exist in the framework of the combined approach.

● The recently discovered states with the hidden charm above $D\bar{D}$-threshold (*XYZ*-particles) have been analyzed. Eleven of these states can be interpreted as charmonium (two singlet $^1S_0$, two singlet $^1D_2$, three triplet $^3S_1$, three triplet ^3P_J and one triplet ^3D_J) and seven as tetraquarks (two neutral and five charged). It has been shown that charge (neutral) tetraquarks must have neutral (charge) partners with mass values which differ by few MeV.

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