NEW PERSPECTIVE FOR STUDY OF EXOTICS
ABOVE $D\bar{D}$ THRESHOLD

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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. Experiments using the antiproton beam have an 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 which were discovered recently. Some of these states can be interpreted as higher-lying charmonium states and tetraquarks. 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.

1 Introduction

The study of strong interactions and hadron matter in the process of antiproton-proton annihilation 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 $\bar{n}\bar{n}g$ and tetraquarks with hidden charm and strangeness ($\bar{n}q\bar{n}q'$, $q$ and $q' = u, d, s$) together with the charmonium 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.

In the last few years we have witnessed the discovery of a number of narrow hadron resonances with charm which do not match the standard quark-antiquark interpretation, thereby named exotic hadrons\(^2,5\). 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 possibility is that new aggregation patterns of quarks in matter are possible. We follow the suggestion of having diquarks as building blocks. Light diquarks have been an object of several lattice studies. The idea that the coloured diquark can be handled as a constituent building block is at the core of the taken approach.

An early quark model prediction was the existence of multiquark states, specifically bound meson antimeson molecular states \(^4,5\). In the light quark sector the $f_0(980)$ and $a_0(980)$ are considered to be strong candidates for $K\bar{K}$ molecules. However, in general, it is challenging to definitively identify a light multiquark state in the environment of many broad and often overlapping conventional states. The charmonium spectrum is better defined so that new types of states can potentially be more easily delineated from conventional charmonium states.
Two generic types of multiquark states have been described in the literature. 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 (although pion exchange is expected to dominate). Molecular states are generally not isospin eigenstates, which give rise to distinctive decay patterns. 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, 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: \( \bar{p}p \rightarrow J/\Psi \rho \rightarrow J/\Psi \pi \pi \); \( \bar{p}p \rightarrow X \rightarrow J/\Psi \omega \rightarrow J/\Psi \pi \pi \pi \); \( \bar{p}p \rightarrow X \rightarrow \chi_{cJ}\pi \) (decays \( J/\Psi, \Psi', \chi_{cJ} \) and light mesons); \( \bar{p}p \rightarrow X \rightarrow DD^* \rightarrow DD\gamma \); \( \bar{p}p \rightarrow X \rightarrow DD^* \rightarrow DD\pi \) (decays into \( DD^*-\)pair). A prediction that distinguishes tetraquark states containing a \( \bar{n}n \) pair from conventional charmonia is possible existence of multiplets which include members with non-zero charge \( \bar{n}u\bar{n}d \), 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 tetraquarks with the hidden charm in the mass region above \( DD \) threshold. The analysis of spectrum of the singlet \( ^1S_0 \), \( ^1P_1 \), \( ^1D_2 \) and triplet \( ^3S_1 \), \( ^3P_J \), \( ^3D_J \) charmonium states and charmed hybrids was carried out earlier. Different decay modes of tetraquarks such as decays into light mesons and decays into \( DD^* \) pair, were, in particular, analyzed. A special attention was given to the new states with the hidden charm discovered recently. The experimental data from different collaborations like Belle, BaBar, LHCb, BES, CDF, CLEO 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, more than twenty tetraquarks were predicted in the mass region above \( DD \) 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 \( Z_c(3885)^\pm, Z_c(3900)^\pm, Z_c(4020)^\pm, Z_c(4050)^\pm, Z_c(4250)^\pm, Z_c(4430)^\pm \) states. The quantum numbers \( J^{PC} \) of the \( X(3872) \) meson have been recently determined by LHCb. One can find that \( X(3872) \) may be interpreted as tetraquark state with \( J^{PC} = 1^{++} \), and \( X(4350) \) may be interpreted as the tetraquark state with \( J^{PC} = 2^{++} \). New state \( Z_c(4430)^\pm \) observed by BES together with the \( Z_c(4050)^\pm, Z_c(4250)^\pm, Z_c(4430)^\pm \) states may be interpreted as charge tetraquarks with \( J^{PC} = 1^{+-} \). New state \( Z_c(4020)^\pm \), observed by BES may be interpreted as charge tetraquark with \( J^{PC} = 0^{++} \). The proposed approach doesn't distinguish the states \( Z_c(3900)^\pm \) and \( Z_c(3885)^\pm \) and as well as \( Z_c(4025)^\pm \) and \( Z_c(4020)^\pm \) states. The values of their masses and widths coincide in the framework of the combined approach. Actually we don’t know whether they are the same state or not. From the physics point of view, it seems that they should be the same. Right now, the masses and widths are obtained from two separate and independent fits. In the future, a couple channel analysis should be performed to derive more reasonable mass and width. The PWA is not done because of the low statistics, so, their \( J^{PC} \) are not determined yet. Two states (one charge and one neutral) with \( J^{PC} = 1^{++} \) are expected to exist in the mass range of 4200–4300 MeV. This hypothesis coincides with that proposed by Maiani and Polosa. But these
assumptions need confirmation in PANDA experiment with its high quality antiproton beam in the channels considered above.

To confirm that the predicted states actually exist and can be found experimentally, their widths and branching ratios were calculated. 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 and tetraquarks as it can be verified by the PANDA experiment. 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 (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 for the PANDA experiment at FAIR.

3 Conclusion

The prospects for future exotics research at FAIR 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.

The most interesting and promising decay channels of tetraquarks have been analyzed. More than twenty tetraquark states above the $D\bar{D}$ 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 (i.e., the XYZ
particles) have been analyzed. Nine of these states can be interpreted as higher-lying tetraquark states. The necessity of further studies of the XYZ particles and improved measurements of their main characteristics in PANDA experiment has been demonstrated.

Using the integral approach for the hadron resonance decay, the widths and branching ratios of the expected states of tetraquarks have been calculated and they turn out to be relatively narrow; most are of the order of several tens of MeV. This fact additionally indicates the necessity of further studying tetraquarks in the channels considered above.

4 Acknowledgments

The authors would like to acknowledge Prof. Dr. Stephen Olsen and Prof. Dr. Vladimir Nikitin for numerous discussions related with this subject.

References