Application of High Quality Antiproton Beam with Momentum Ranging from 1 GeV/c to 15 GeV/c to Study Charmonium and Charmed Hybrids

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The elaborate analysis of spectrum of charmonium states and charmed hybrids in the mass region over $D\overline{D}$-threshold is given. The combined approach based on the potential model and relativistic spherical symmetric top model for decay products has been proposed. The experimental data from different collaborations were analyzed. Especial attention was given to the new states with the hidden charm discovered recently. Eight of these states may be interpreted as higher laying radial excited charmonium states. But much more data on different decay modes are needed for deeper analysis. These data can be derived directly from the experiments using high quality antiproton beam with the momentum ranging from 1 GeV/c to 15 GeV/c (PANDA experiment at FAIR).

1   Introduction

The study of charmonium and charmed hybrids spectroscopy is one of the main domains of elementary particle physics. It seems to be a challenge nowadays. The research of charmonium (the system consisting of charmed quark-antiquark pair $c\bar{c}$) and charmed hybrids (the system consisting of charmed quark-antiquark pair strongly interacting with gluonic component $c\bar{c}$g) using the antiproton beam with momentum ranging from 1 GeV/c to 15 GeV/c in PANDA experiment at FAIR is perspective and interesting from the scientific point of view. Charmonium and charmed hybrids with different quantum numbers are copiously produced in antiproton-proton annihilation process. The accuracy of mass and width measurements depends only on the quality of antiproton beam (high luminosity, minimal beam momentum spread, small lateral beam dimension). It becomes possible to extract the information about excited states of charmonium which can be extremely useful for understanding the nature of strong interactions. The performed analysis of charmonium is promising to understand the dynamics of quark interactions at small distances [1].


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2 Results of calculations

The charmonium system has been investigated in detail, first, in e^+e^--reactions, and afterwards — on a restricted scale but with high precision — in $\overline{p}p$-annihilations (the experiments R704 at CERN and E760/E835 at Fermilab). Nowadays the scalar $^1D_2$ and vector ^3D_J charmonium states are not established. The higher laying scalar $^1S_0$, $^1P_1$ and vector $^3S_1$, ^3P_J charmonium states are badly investigated [2]. The domain over $D\overline{D}$-threshold of 3.73 GeV/c^2 is poorly studied. According to the contemporary quark models (LQCD, flux tube model), namely in this domain, the existence of charmed hybrids with exotic ($J^{PC} = 0^{+-}, 1^{-+}, 2^{+-}$) as with non-exotic ($J^{PC} = 0^{-+}, 1^{+-}, 2^{-+}, 1^{++}, 1^{--}$) quantum numbers is expected [1,2].

The elaborated analysis of spectrum of the scalar ($^1S_0, ^1P_1, ^1D_2$), vector ($^3S_1, ^3P_J, ^3D_J$) charmonium states and charmed hybrids with exotic and non-exotic quantum numbers in the mass region mainly over $D\overline{D}$-threshold, has been fulfilled [3,4]. Different decay modes of charmonium such as decays into particle-antiparticle or $D\overline{D}$-pair, decays into light hadrons and decays with J/ψ in the final state were investigated. Concerning the charmed hybrids, the decays into charmonium and light mesons in the final state and decays into $D\overline{D}^*$-pair, were, in particular, analyzed. These modes possess small widths and significant branching ratios. This fact facilitates their experimental detection.

Using the combined approach based on the quarkonium potential model and relativistic top model for decay products, ten new radial excited states of charmonium were predicted in the mass region over $D\overline{D}$-threshold equal to 3.73 GeV/c^2. Sixteen charmed hybrids (lowest-laying hybrids and their radial excited states) are expected to exist in the discussed mass region. A special attention is given to the new states with the hidden charm discovered recently (XYZ-particles) [5,6]. The experimental data from different collaborations (Belle, BaBar, CLEO, CDF) were carefully analyzed. It has been found that eight of new recently discovered states may be interpreted as charmonium states (two scalar $^1S_0$, three vector $^3S_1$ and tree vector ^3P_J). But much more data on different decay channels (modes) are needed for deeper analysis. These data can be derived directly from PANDA experiment with its high quality antiproton beam. Hence, there is a possibility of measuring the masses, widths and branching ratios of different charmonium and charmed hybrid states with high accuracy.

Figure 1 illustrates the spectrum of scalar $^1S_0$ and vector $^3S_1$, ^3P_J states of charmonium. Black boxes correspond to the established charmonium states, black-white boxes — recently experimentally revealed states with the hidden charm (XYZ-particles) that may be interpreted as higher laying charmonium states. Possible existence of charmonium states marked by black-white boxes was predicted in our recent calculations. One can find that $X(3940)$ and $X(4160)$ can be interpreted as radial excited scalar $^1S_0$ states of charmonium; $Y(4260)$, $Y(4360)$ and $Y(4660)$ — as radial excited vector $^3S_1$ states of charmonium and $X(3915)$, $Y(3940)$, $Z(3930)$ — as radial excited vector ^3P_J states of charmonium. Finally, white boxes correspond to the states which are not found yet. But a possibility of existence

of these states is predicted in the framework of the combined approach. They may also be interpreted as higher laying radial excited states of charmonium.
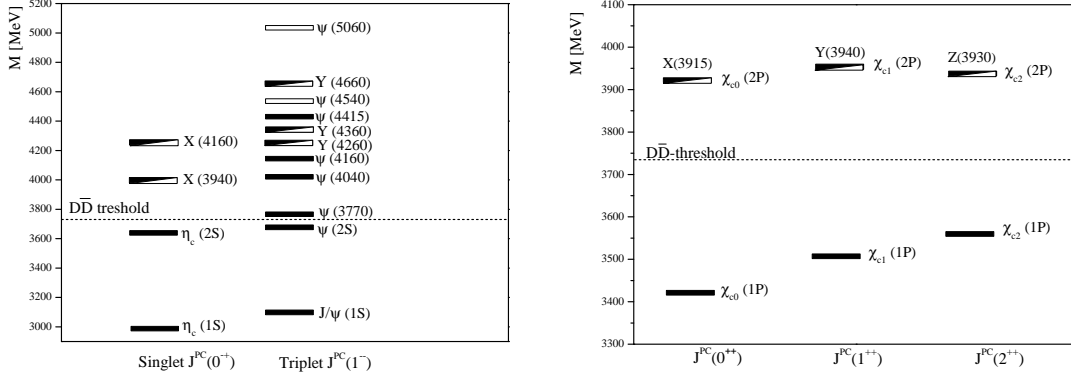
Figure 1: The spectrum of scalar $^1S_0$ and vector $^3S_1$ and ^3P_J states of charmonium.
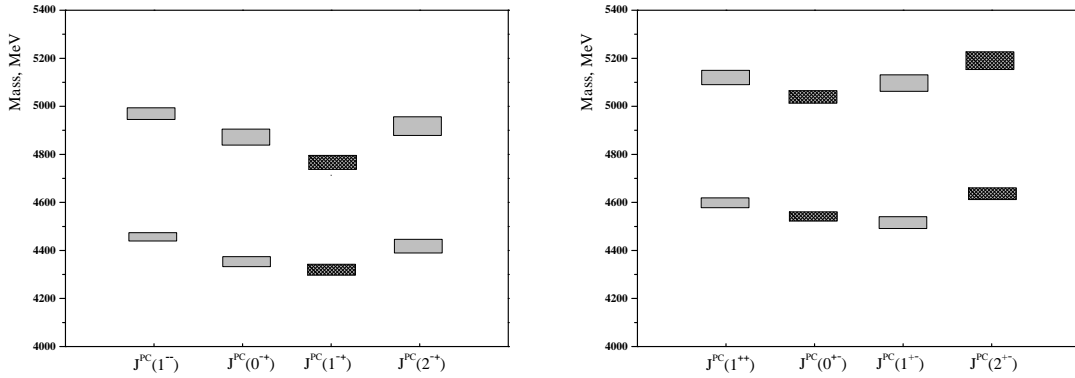
Figure 2: The spectrum of charmed hybrids with quantum numbers $J^{PC} = 2^{-+}, 1^{-+}, 1^{--}, 0^{-+}$ and $2^{+-}, 1^{+-}, 1^{++}, 0^{+-}$.

Figure 2 illustrates the spectrum of the lowest-laying charmonium hybrids and their radial excited states. Charmed hybrids with exotic quantum numbers are marked with dark colour and charmed hybrids with nonexotic quantum numbers — with light colour. One can find that the state with exotic quantum numbers $J^{PC} = 1^{-+}$ has the lowest mass equals to 4320 MeV/c^2. The results of calculations 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 expected splitting is about $150 - 250$ MeV/c^2.

To be sure that the predicted charmonium and charmed hybrid states can really exist and can be found experimentally, their widths have been calculated [3, 4]. The values of widths are of an order of several tens of MeV. This fact facilitates their experimental search.

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3 Conclusions

Finally the progress of the future charmonium and charmed hybrids researches at FAIR is related to the results obtained below:

• A combined approach has been proposed to study charmonium and charmed hybrids on the basis of quarkonium potential model and relativistic top model for decay products.

• Several promising decay channels of charmonium like decays into light hadrons $\overline{p}p \to c\overline{c} \to \rho\pi$, decays into particle-antiparticle $\overline{p}p \to c\overline{c} \to \Sigma^0\overline{\Sigma}^0$, decays into $D\overline{D}$-pair and decays with J/ψ in the final state $\overline{p}p \to c\overline{c} \to J/\Psi + X$, were, in particular, analyzed.

• Ten radial excited states of charmonium (two scalar $^1S_0$, three vector $^3S_1$ and tree vector ^3P_J) above $D\overline{D}$-threshold have been predicted in the framework of the combined approach.

• Several promising decay channels of the charmed hybrids like decays into charmonium and light mesons in the final state $\overline{p}p \to c\overline{c}g \to \chi_{c0,1,2}(\eta, \pi\pi; ...)$, $\overline{p}p \to c\overline{c}g \to J/\Psi(\eta, \omega, \pi\pi; ...)$ and decays into $D\overline{D}^*$-pair $\overline{p}p \to c\overline{c}g \to D\overline{D}^*\eta$ were considered.

• Sixteen charmed hybrids with exotic and nonexotic quantum numbers are expected to exist in the framework of the combined approach.

• The recently discovered XYZ-particles have been analyzed. Some of these states can be interpreted as higher laying radial excited states of charmonium. The necessity of further studying the XYZ-particles and their main characteristics in PANDA experiment at FAIR has been demonstrated.

References

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