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SEARCH FOR HIGHER LYING CHARMONIUM STATES AND CHARMED HYBRIDS IN EXPERIMENTS USING ANTIPROTON BEAM WITH MOMENTUM RANGING FROM 1 TO 15 GeV/c

M. Yu. Barabanov, A. S. Vodopyanov, V. Kh. Dodokhov

Joint Institute for Nuclear Research, Dubna

The elaborated analysis of spectrum of scalar and vector charmonium states in the mass region above $D\bar{D}$-threshold is given. The combined approach based on the potential model and relativistic spherical symmetric top model for decay products has been proposed. Ten radial excited states of charmonium in the mass region above $D\bar{D}$-threshold are anticipated to exist in the framework of the combined approach. The experimental data from different collaborations were analyzed. Special attention was given to the new states with the hidden charm discovered recently. Eight of these states may be interpreted as higher lying 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 to 15 GeV/c (PANDA experiment at FAIR).

Проведен тщательный анализ спектра скалярных и векторных состояний чармония в области выше порога рождения $D\bar{D}$-пары. Предложен комбинированный подход, основанный на потенциальной модели и модели релятивистского сферически-симметричного волчка для продуктов распада. Ожидается существование десяти новых радиально возбужденных состояний чармония выше порога рождения $D\bar{D}$-пары в рамках комбинированного подхода. Проанализированы экспериментальные данные, полученные различными коллаборациями. Особое внимание авторы обратили на новые, недавно обнаруженные состояния со скрытым шармом. Восемь из таких состояний могут быть интерпретированы как высоколежащие радиально возбужденные состояния чармония. Но для более глубокого анализа требуется намного большее количество экспериментальных данных по различным каналам распада. Эти данные могут быть получены непосредственно из экспериментов на пучке антипротонов с импульсом от 1 до 15 ГэВ/c (эксперимент PANDA на установке FAIR).

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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 (the system consisting of charmed quark–antiquark pair $c\bar{c}$), charmed hybrids (the system consisting of charmed quark–antiquark pair strongly interacting with gluonic component $\bar{c}g$), spectra and their main characteristics: mass, width, and branch ratios in experiments using antiproton beam with momentum ranging from 1 to 15 GeV/c, are promising to understand the dynamics of quark interactions at small distances. Charmonium spectroscopy is a good testing tool for the theories of strong interactions: QCD in both perturbative and nonperturbative regimes, QCD inspired purely phenomenological potential models, nonrelativistic QCD and LQCD [1].

The elaborate analysis of charmonium spectrum was carried out, and the attempts to interpret a great quantity of experimental data above $D\bar{D}$-threshold were considered. But much more data on different decay modes are needed for a deeper analysis. These data can be derived directly from PANDA experiment with its high-quality antiproton beam. The advantage of antiproton beam consists in intensive production of particle–antiparticle pairs which is observed in antiproton–proton annihilation. This fact allows one to carry out spectroscopic research with good statistics and high accuracy. Hence, there is a possibility of measuring the masses, widths, and branch ratios of different charmonium states with high accuracy.

Nowadays the scalar $^1D_2$ and vector ^3D_J charmonium states are not established. The higher laying scalar $^1S_0$ (η), $^1P_1(h_c)$ and vector $^3S_1$ (ψ), ^3P_J $(\chi_{0,1,2})$ charmonium states are poorly investigated [2]. The domain above $D\bar{D}$-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 well as with nonexotic ($J^{PC} = 0^{-+}$, 1^{+-}, 2^{-+}, 1^{++}, 1^{--}) quantum numbers is expected [1].

During the last several years nearly twenty new states (the so-called X, Y, Z particles) with the hidden charm were discovered by different experimental groups (Belle, BaBar, CLEO, CDF). Their interpretation is ambiguous nowadays. Most of these states were observed over the $D\bar{D}$-threshold in some definite channel (beside $X(3872)$-state). New particles were produced from B-meson decays (B-factory) and in electron–positron or two-photon collisions [3–6].

A combined approach based on the quarkonium potential model and relativistic spherical symmetric top model for decay products has been proposed to calculate the mass spectrum of radial excited states of charmonium and charmed hybrids. One assumes that the decay potential has the finite radius beyond which the decaying charmonium or charmed hybrid are considered as collection of two relativistic tops in the same quantum state [7–10].

In general, one can identify four main classes of charmonium decays [1]:

— decays into particle–antiparticle or $D\bar{D}$-pair: $(p\bar{p} \to \Psi$, η_c, $\chi_{cJ}) \to$ barion–antibaryon or $D\bar{D}$-pair;

— decays into light hadrons: $p\bar{p} \to \Psi \to \rho\pi$, $p\bar{p} \to \eta_c \to \rho\pi$, $\Psi \to \pi^+\pi^-$, $\Psi \to \omega\pi^0, \ldots$;

— radiative decays: $p\bar{p} \to \gamma\eta_c$, $\gamma\chi_{cJ}$ (are employed for h_c, η_c and their radial excitations study);

— decays with J/Ψ in the final state (production and formation experiments): $p\bar{p} \to J/\Psi + X \Rightarrow p\bar{p} \to J/\Psi\pi^+\pi^-$, $p\bar{p} \to J/\Psi\pi^0\pi^0$ (are employed to study χ_{cJ} and radial excitations of Ψ and χ_{cJ}).

CALCULATION OF CHARMONIUM MASS SPECTRUM

The most interesting decay channels of charmonium (from theoretical and experimental viewpoints) $p\bar{p} \to c\bar{c} \to \rho\pi$, $p\bar{p} \to c\bar{c} \to \Sigma^0\bar{\Sigma}^0$, decays into $D\bar{D}$-pair, and decays with J/Ψ in the final state $p\bar{p} \to J/\Psi + X$, were, in particular, considered [9, 10]. The masses of the particles participating in charmonium formation and decay are known with high precision.

For this purpose the elaborate analyses of the scalar and vector charmonium states in the mass region mainly above $D\bar{D}$-threshold, has been fulfilled. The mass spectra of the radial excited scalar and vector charmonium states were calculated in the framework of the combined approach up to the B-meson mass range [9, 10]. Especial attention was given to the new states with the hidden charm discovered recently. The experimental data from different collaborations (Belle, BaBar, CLEO, CDF) were carefully analyzed [3–6]. 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 above $D\bar{D}$-threshold equal to 3.73 GeV/c [9, 10]. It has been found that this approach not only predicts new states, but describes the existing experimental data with high accuracy. It was established that eight of the new recently discovered states (X, Y, Z particles) can be interpreted as charmonium states (two scalar $^1S_0$, three vector $^3S_1$, and three vector ^3P_J charmonium states). But much more data on different decay modes (decay channels) are needed for deeper analysis. These data can be derived directly from PANDA experiment with its high-quality antiproton beam. The advantage of antiproton beams consists in intensive production of particle–antiparticle pairs which is observed in antiproton–proton annihilation. This fact allows one to carry out spectroscopic research with good statistics and high accuracy. Hence, there is a possibility of measuring the masses, widths and branch ratios of different charmonium states with high accuracy.

Figures 1, 2 illustrate the possible 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, to recently experimentally revealed states. The possible existence of the states marked by black–white boxes was predicted in our recent calculations [9, 10]. One can find that $X(3940)$ and $X(4160)$ can be interpreted as radial excited scalar $^1S_0$ states of charmonium; $Y(4260)$, $Y(4350)$ 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,

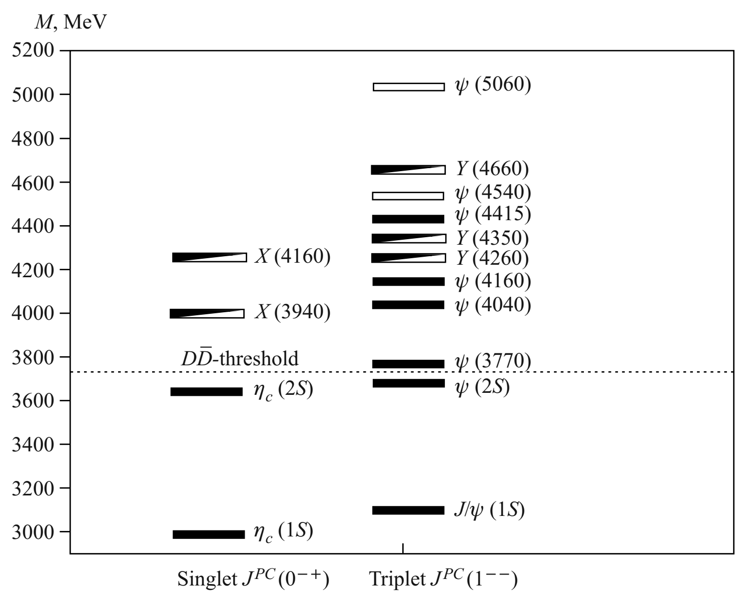

Fig. 1. The spectrum of scalar $^1S_0$ and vector $^3S_1$ states of charmonium

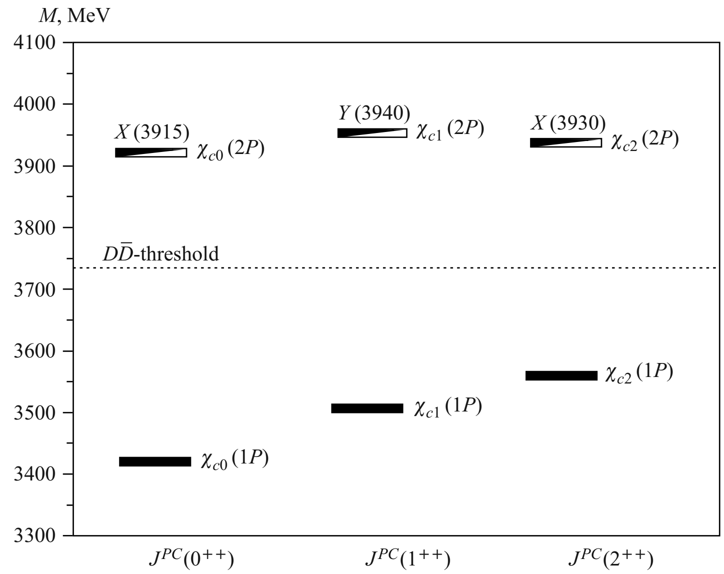

Fig. 2. The spectrum of vector ^3P_J states of charmonium

white boxes correspond to the states which are not found yet. But possibility of existence of these states is predicted in the combined approach. They can also be interpreted as radial excited states of charmonium.

CALCULATION OF WIDTHS OF CHARMONIUM STATES

The integral formalism or integral approach [11, 12] is based on the possibility of the appearance of discrete quasi-stationary states (levels) with finite values of the width at the positive energy domain in the case of barrier-type potentials formed by means of superposition of two types of potentials: short-range attractive potential $V_1(r)$ and long-range repulsive potential $V_2(r)$.

The width of the quasi-stationary state in the integral approach is defined by the equation:

$$\Gamma = 2\pi \left| \int \varphi_L(r)\, V_1(r) F_L(r) r^2\, dr \right|^2,$$

where $F_L(r)$ is the regular decision in potential field $V_2(r)$, normalized at the energy delta function; $\phi_L(r)$ is the normalized wave function of the stationary state, corresponding to the resonance state and tending far from internal turning point to the irregular decision in the potential field $V_2(r)$.

The application of the integral approach to calculate the widths of the scalar and vector charmonium states gives the results which are in good agreement with the experimental data. The widths of the predicted and recently discovered charmonium states vary from several tens of MeV to one hundred MeV [9, 10]. This fact is the feature of all the known charmonium states.

CONCLUSION

The progress of future charmonium researches at FAIR is related to the results presented below:

• The approach to study the charmonium and charmed hybrids spectra based on the quarkonium potential model and relativistic spherical symmetric top model for decay products, has been offered.

• One can find that this approach describes the existing experimental data with high accuracy. The results of the calculations coincide with the existing experimental data in the range of the experimental error.

• Several promising decay channels of charmonium like: $p\bar{p} \to c\bar{c} \to \rho\pi$, $p\bar{p} \to c\bar{c} \to \Sigma^0\bar{\Sigma}^0$, decays into $D\bar{D}$-pair and decays with J/ψ in the final state $p\bar{p} \to J/\psi + X$ were investigated.

• Ten radial excited states of charmonium (two scalar and eight vector states) above $D\bar{D}$-threshold are anticipated to exist in the framework of the combined approach.

• A possibility to confirm their existence and verify their main characteristics in PANDA experiment with the high-quality antiproton beam, has been demonstrated.

• The recently discovered states above $D\bar{D}$-threshold (X, Y, Z particles) have been elaborately analyzed. Some of these states can be interpreted as higher lying radial excited states of charmonium. This treatment seems to be perspective and needs to be carefully verified in the future PANDA experiment with its high-quality antiproton beam.

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