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Perspectives of the study of charmonium and charmed hybrid spectra above $D\bar{D}$ threshold using the antiproton beam with momentum ranging from 1 GeV/c to 15 GeV/c

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The spectroscopy of charmonium $c\bar{c}$ and charmed hybrids $c\bar{c}g$ is discussed. Charmonium studies are promising for understanding the dynamics of quark interaction at small distances. It is a good testing tool for the theories of strong interactions: QCD in both perturbative and non-perturbative regimes, Lattice QCD (LQCD), potential models and phenomenological models. The study of strong interactions and hadronic matter in the process of antiproton-proton annihilation seems to be a perspective nowadays. For this purpose the analysis of charmonium and charmed hybrids spectrum is given, and the attempts to interpret a great quantity of experimental data above $D\bar{D}$ threshold are considered. Advantages of the antiproton beam consist in intensive production of particle-antiparticle pairs which is observed in antiproton-proton annihilation. The experimental data from different collaborations have been analyzed. Especial attention was given to the new states with hidden charm discovered recently. Some of these states may be interpreted as higher laying charmonium states. But much more data on different decay modes are needed for a deeper analysis. These data can be derived directly from the experiments using the high quality antiproton beam with the momentum ranging from 1 GeV/c to 15 GeV/c.

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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 [1, 2]. 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. The size of charmonium is of the order of less than 1 fm, so that one of the main properties of QCD, asymptotic freedom, is emerging. Charmonium spectroscopy is a good testing tool for the theories of strong interactions: QCD in both perturbative and non-perturbative regimes; QCD inspired purely phenomenological potential models; non-relativistic QCD and LQCD.

The elaborate analysis of charmonium and charmed hybrids spectra was carried out, and the attempts to interpret a great quantity of experimental data above $D\bar{D}$ - threshold were undertaken. 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 branching ratios of different charmonium and charmed hybrid states with high accuracy.

The charmonium system has been investigated in detail, first, in e^+e^--reactions, and afterwards - on a restricted scale but with high precision - in $\bar{p}p$-annihilations (the experiments R704 at CERN and E760/E835 at Fermilab). Despite these efforts a number of unsolved questions dealing with charmonium has remained:

- singlet $^1D_2$ and triplet ^3D_J charmonium states have not been determined yet;
- the higher laying singlet $^1S_0$, $^1P_1$ and triplet $^3S_1$, ^3P_J – charmonium states above $D\bar{D}$ threshold are poorly investigated;
- only few partial widths of ^3P_J states are known (some of the measured decay widths don't fit theoretical schemes and additional experimental check or reconsideration of the corresponding theoretical models is needed, more data on different decay modes are desirable to clarify the situation);
- the domain above $D\bar{D}$ threshold of 3.73 GeV/c^2 is poorly studied.

During the last several years about twenty new states (the so called *XYZ*-particles) with the hidden charm were discovered by different experimental groups like Belle, BaBar, BES, CLEO, CDF, D0. Most of these states were observed above $D\bar{D}$ threshold in some definite channel (beside *X(3872)* and *Y(4260)* states). 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].

In general one can identify four main classes of charmonium decays which are especially interesting and promising from the scientific point of view [1, 5]:

- decays into particle-antiparticle or $D\bar{D}$ pair: $\bar{p}p \to (\Psi, \eta_c, \chi_{cJ}) \to$ baryon-antibaryon or $D\bar{D}$ pair;
- decays into light hadrons: $\bar{p}p \to \Psi \to \rho\pi$, $\bar{p}p \to \eta_c \to \rho\pi$, $\bar{p}p \to \Psi \to \pi^+\pi^-$, $\bar{p}p \to \Psi \to \omega\pi^0$,…;
- radiative decays: $\bar{p}p \to \gamma\eta_c, \gamma\chi_{cJ}$ ...; (are employed mainly for h_c, η_c and their radial excitations study);
- decays with J/Ψ or Ψ' in the final state: $\bar{p}p \to c\bar{c} \to (J/\Psi, \Psi') + X$ => $\bar{p}p \to c\bar{c} \to (J/\Psi, \Psi')\pi^+\pi^-$, $\bar{p}p \to c\bar{c} \to (J/\Psi, \Psi')\pi^0\pi^0$ (are employed mainly to study χ_{cJ} and radial excitations of Ψ and χ_{cJ}).

Charmed hybrids are states with an excited gluonic degree of freedom. These states are described by different models and calculation schemes. All model predictions and calculations agree that the mass of the lowest-laying charmonium hybrids are between 3.9 and 4.6 GeV/c^2 and that the state with $J^{PC} = 1^{-+}$ has the lowest mass [1, 2]. The mass splitting is caused by spin-dependent effects which are not well known. Energy difference of some tens of MeV between the states seems to be realistic, but the experimental determination would yield valuable insights into the nature of the spin-dependent effects which cause them.

Until now, discussions have been focused only around the lowest-laying 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. Three of these eight charmonium hybrids have spin-exotic quantum numbers ($J^{PC} = 1^{-+}, 0^{+-}, 2^{+-}$), so mixing effects with nearby $c\bar{c}$ states are excluded for them thus making their experimental identification especially easy.

In principle, non-exotic hybrid states can mix with $c\bar{c}$ states if they have the same quantum numbers and their masses overlap. Such mixing can change their predicted masses and widths, and is considered to be important for light hybrids. This is much less of a problem for charmed hybrids, because there are only several $c\bar{c}$ states and they have much smaller widths than $q\bar{q}$ states (*q* denotes *u* and *d* quarks).

The selection of final states is used as a quantum-number filter for the decaying hybrid. Charmonium hybrids predominantly decay via electromagnetic and hadronic transitions and into the open charm final states [1, 2, 3, 4]:

- $c\bar{c}g \to c\bar{c}$ (Ψ, χ_{cJ}) + light mesons ($\eta, \eta', \omega, \varphi$) - these modes supply small widths and significant branching ratios;

- $c\bar{c}g \rightarrow D\overline{D}_J^{\,*}$ - in this case D(L = 0) + $\overline{D}_J^{\,*}$(L = 1) final states should dominate over decays to $D\overline{D}$ and the partial width to $D\overline{D}_J^{\,*}$ should be very small.

The most interesting and promising decay channels of charmed hybrids are as follows:

- $\bar{p}p \rightarrow \tilde{\eta}_{c0,1,2}\ (0^{-+}, 1^{-+}, 2^{-+})\ \eta \rightarrow \chi_{c0,1,2}\,(\eta,\ \pi\pi;\ldots)$;
- $\bar{p}p \rightarrow \tilde{h}_{c0,1,2}\ (0^{+-}, 1^{+-}, 2^{+-})\ \eta \rightarrow \chi_{c0,1,2}\,(\eta,\ \pi\pi;\ldots)$;
- $\bar{p}p \rightarrow \tilde{\Psi}\,(1^{--}) \rightarrow J/\Psi\,(\eta,\ \omega\ ,\ \pi\pi, \ldots)$;
- $\bar{p}p \rightarrow \tilde{\eta}_{c0,1,2}, \tilde{h}_{c0,1,2}, \tilde{\chi}_{c1}\ (0^{-+}, 1^{-+}, 2^{-+}, 0^{+-}, 1^{+-}, 2^{+-}, 1^{++})\ \eta \rightarrow D\overline{D}_J^{\,*}\eta$.

1.1 Discussion of the results of calculation for charmonium and charmed hybrids.

For this purpose a detailed 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 with exotic and non-exotic quantum numbers in the mass region above $D\overline{D}$ threshold, has been performed. 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 and 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 $D\overline{D}_J^{\,*}$ 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 [6, 7], ten new radial excited states of charmonium were predicted in the mass region above $D\overline{D}$ threshold (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. It has been found that this approach not only predicts new states, but describes the existing experimental data with high accuracy. A special attention is given to the new states with the hidden charm discovered recently (*XYZ*-particles). The experimental data from different collaborations (Belle, BaBar, CLEO, CDF, BES, D0) were carefully analyzed. It has been found that eight of new recently discovered states may be interpreted as charmonium states (two singlet $^1S_0$, three triplet $^3S_1$ and tree triplet ^3P_J). But much more data on different decay channels (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 branching ratios of different charmonium and charmed hybrid states with high accuracy.

Figures 1, 2 illustrate the spectrum of singlet $^1S_0$ and triplet $^3S_1$, ^3P_J states of charmonium. Black boxes correspond to the established charmonium states, black-white boxes – recently experimentally discovered 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 [6, 7]. One can find that *X(3940)* and X*(4160)* can be interpreted as radial excited singlet $^1S_0$ states of charmonium; *Y(4260)*, *Y(4360)* and *Y(4660)* - as radial excited triplet $^3S_1$ states of charmonium and *X(3915)*, *Y(3940), Z(3930)* – as radial excited triplet ^3P_J states of charmonium. Finally, white boxes correspond to the states which have not been 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 [8].

Figures 3, 4 illustrate 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 equal 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 200 MeV/c^2.

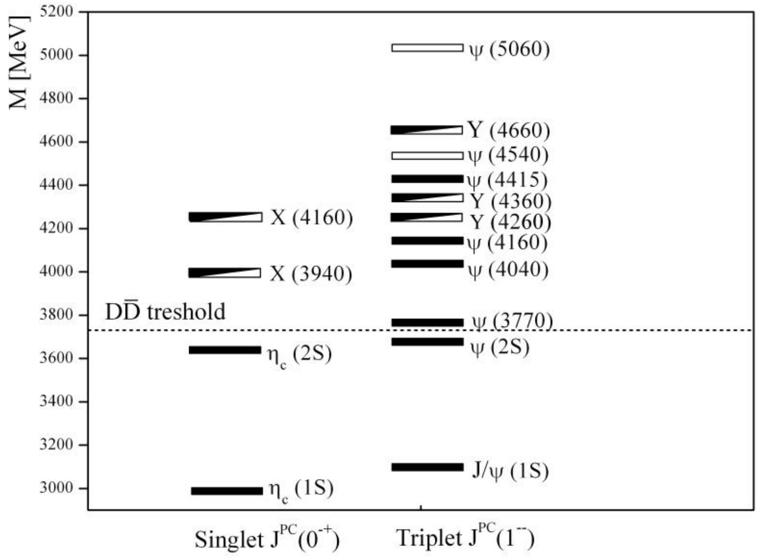

Fig.1. The spectrum of scalar $^1S_0$ and vector $^3S_1$ states of charmonium.

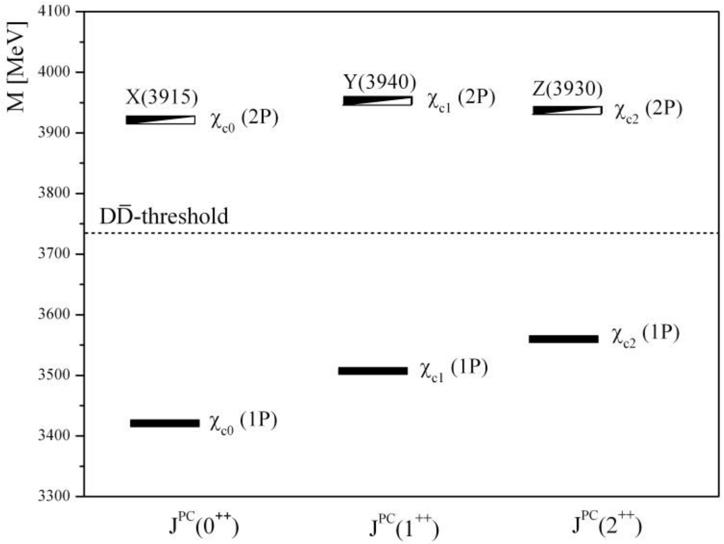

Fig.2. The spectrum of vector ^3P_J states of charmonium

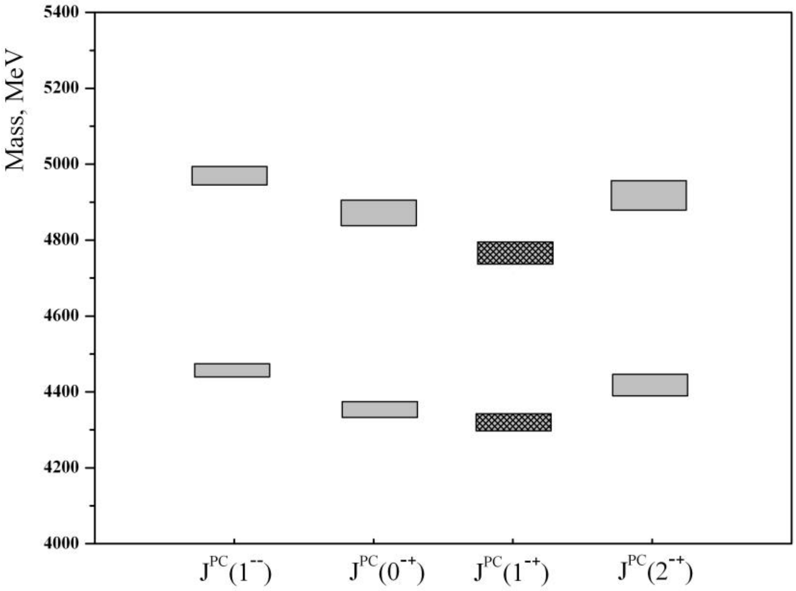

Fig.3. The spectrum of charmed hybrids with quantum numbers $J^{PC} = 2^{-+}, 1^{-+}, 1^{--}, 0^{-+}$.

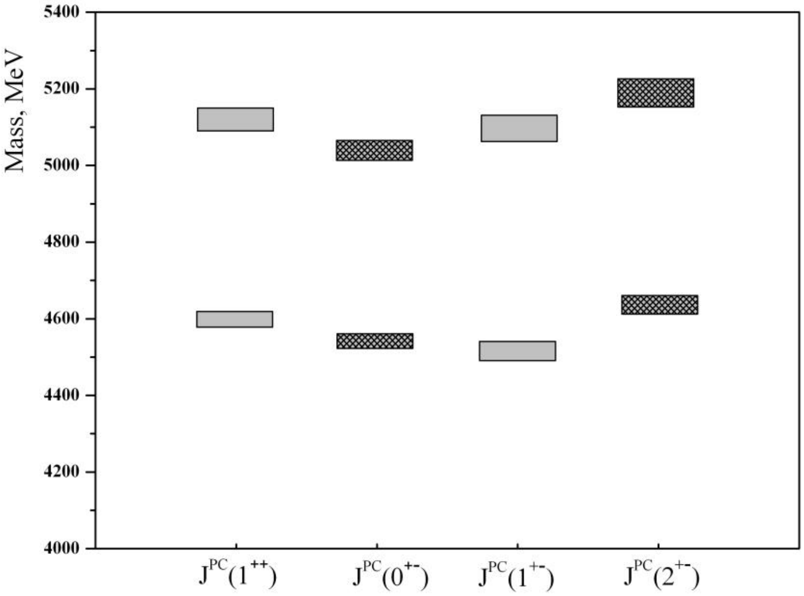

Fig.4. The spectrum of charmed hybrids with quantum numbers $J^{PC} = 2^{+-}, 1^{+-}, 1^{++}, 0^{+-}$.

1.2. Calculation of the widths of charmonium and charmed hybrids.

To make the experimental identification of the predicted charmonium and charmed hybrid states easier their widths and branching ratios have been calculated. The feature of all charmonium and charmed hybrid states is their narrowness compared with light unflavored mesons, baryons and hybrids. These states have small widths. Their values vary from several tens of keV to several tens of MeV. This fact facilitates their experimental search. Therefore the results of calculation of charmonium widths must confirm the experimentally established values and have the values of the predicted charmonium states also of an order of several tens of MeV (except few predicted higher laying charmonium states with the width equal to ≈ 100 MeV). In other words, the charmonium widths must be narrow and not have anomalous large values.

The integral approach (integral formalism) for the hadron resonance decay [9, 10] was applied to calculate the widths of the scalar and vector charmonium states [7, 8] and charmed hybrids. This approach is based on the possibility of the appearance of discrete quasistationary 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 quasistationary state in the integral approach is given by the equation (integral formula) [9, 10]:

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

$$(r < R) : \int_0^R \left| \phi_L(r) \right|^2 dr = 1,$$

where $F_L(r)$– is the regular decision in potential field $V_2(r)$, normalized at the energy delta function, $\varphi_L(r)$–normalized wave function of the stationary state, corresponding to the resonance state and tends far from the internal turning point to the irregular decision in the potential field $V_2(r)$. The integral can be calculated with the well known approximation methods: for example, the saddle-point technique or other numerical methods.

The application of the integral approach to calculate the widths of the scalar and vector charmonium states gives results which are in good agreement with the existing experimental data [7, 8]. The values of the widths of predicted charmonium states coincide (within the experimental error) with the experimentally established values for the *XYZ*-particles. The coincidence of the values of their masses has been discussed above. This fact additionally demonstrates that some of the *XYZ*-particles may be interpreted as higher laying charmonium states and needs to be carefully verified in PANDA experiment [7, 8].

Figs. 5, 6 illustrate the results of calculation of the widths of charmed hybrids through the considered decay channels: the decays into charmonium and light mesons and decays into $D\overline{D}_J^*$ pair. One can find that the widths of charmed hybrids are narrow with the values of an order of several tens of MeV. This fact is the feature of the charmonium and charmed hybrid states as it was discussed above.

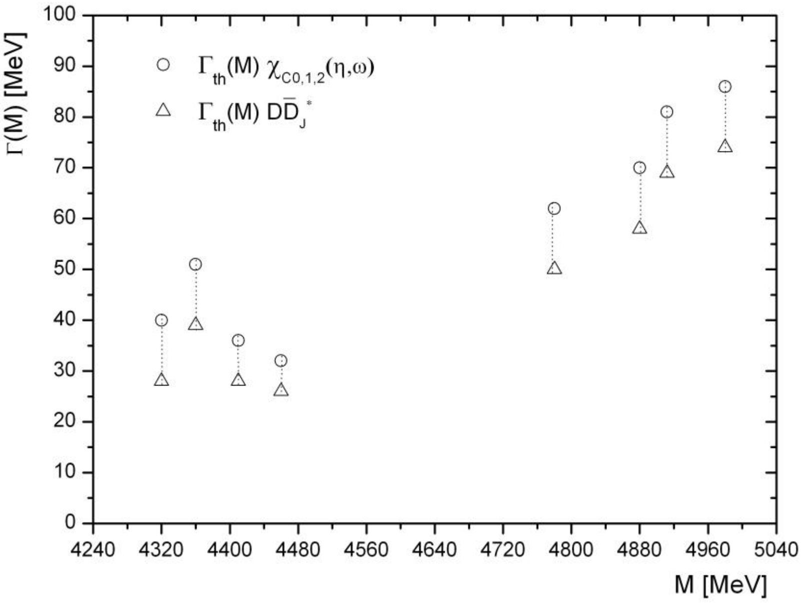

Fig.5. The widths of the charmed hybrids with quantum numbers J^{PC} = 2^{-+}, 1^{-+}, 1^{--}, 0^{-+}.

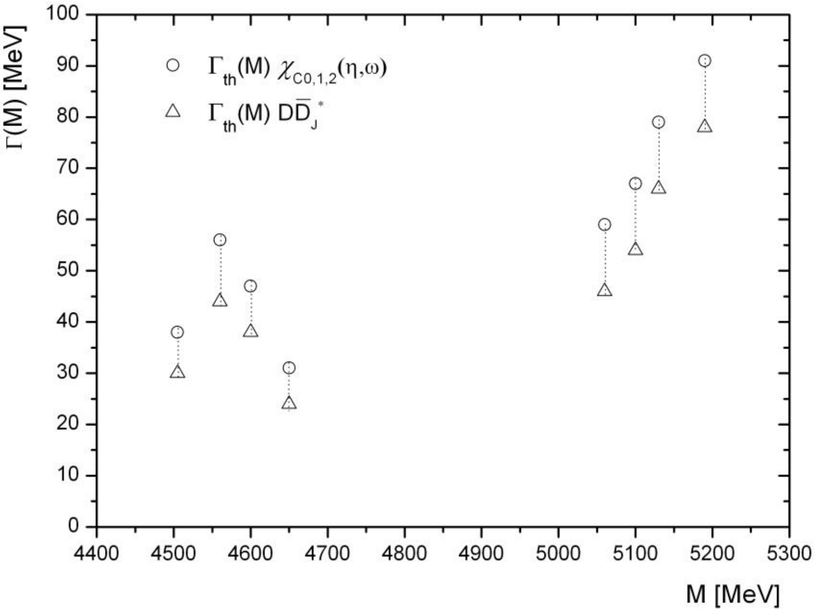

Fig. 6. The widths of the charmed hybrids with quantum numbers J^{PC} = 2^{+-}, 1^{+-}, 1^{++}, 0^{+-}.

1.3. Conclusion.

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

■ The most interesting and promising decay channels of charmonium like the decays into light hadrons $\bar{p}p \rightarrow c\bar{c} \rightarrow$ ($\rho\pi$, $\omega\pi^0$, $\eta\pi^0$, $\pi\pi$), decays into particle-antiparticle

$\bar{p}p \to c\bar{c} \to (\Sigma^0\overline{\Sigma^0},\ \Lambda\bar{\Lambda})$, decays into $D\bar{D}$ pair, decays with J/Ψ and Ψ' in the final state $\bar{p}p \to c\bar{c} \to J/\Psi + X$, $\bar{p}p \to c\bar{c} \to \Psi' + X$, have been analyzed.

■ Ten radial excited states of charmonium (two scalar $^1S_0$, three vector $^3S_1$ and tree vector ^3P_J) above $D\bar{D}$ threshold are anticipated to exist 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 $\bar{p}p \to c\bar{c}g \to \chi_{c0,1,2}$ $(\eta,\ \pi\pi;\ldots)$, $\bar{p}p \to c\bar{c}g \to J/\Psi\ (\eta,\ \omega,\ \pi\pi;\ldots)$ and decays into $D\bar{D}_J^*$ pair $\bar{p}p \to c\bar{c}g \to D\bar{D}_J^*\ \eta$ were, in particular, considered.

■ Sixteen charmed hybrids (lowest-laying charmonium hybrids and their radial excited states) with exotic and nonexotic quantum numbers 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. Some of these states can be interpreted as higher laying radial states of charmonium. The necessity of further studying the *XYZ*-particles and their main characteristics (mass, width, branching ratio) in PANDA experiment with its high quality antiproton beam, has been demonstrated.

■ Using the integral approach for the hadron resonance decay, the widths of the predicted states of charmonium and charmed hybrids have been calculated. One can find that these states are narrow. Their widths don't have anomalous large values and are of the order of several tens of MeV.

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