How much charm can $\bar{P}ANDA$ produce

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Heavy hadrons consisting of a charm quark are quite distinct in their properties from the light flavored hadrons composed of up (u), down (d), and strange (s) quarks. The presence of the heavy quark in heavy flavor hadrons provides an additional handle for the understanding of quantum chromodynamics (QCD), the fundamental theory of the strong interaction. Within the range of momentum exchange in bound $c\bar{c}$ systems, the value of the strong coupling constant α_s is not so large to invalidate the application of the perturbative methods. Thus these states provide a unique laboratory to explore the interplay between perturbative and non-perturbative effects in QCD. The relatively small binding energy of the charmonium state as compared to the rest mass of its constituents allows its description by the non-relativistic approaches that simplify and constrain the analysis of the non-perturbative effects. These mostly analytical methods are of considerable help in making significant progress in lattice QCD calculations, which have become increasingly more capable of dealing quantitatively with the non-perturbative dynamics in all its aspects (see, e.g., the Refs. [1]). The large mass of the charm quark introduces a mass scale much larger than the confinement scale $\Lambda_Q \approx 300$ MeV, which is in contrast, the energy scale of the lighter quarks is $\ll \Lambda_Q$. The presence of two scales in such systems naturally leads to the construction of an effective theory where one can actually calculate a big portion of the relevant physics using perturbation theory techniques.

Therefore, there is considerable interest in investigations of the production of charm hadron states in nuclear collisions. Since the discovery of J/ψ [2, 3], the production of charmonium states ($c\bar{c}$) has been studied extensively mainly in electron-positron and proton-antiproton annihilation processes. However, there are distinct advantages in producing $c\bar{c}$ states in the latter method where all the three valence quarks in a proton annihilate with their corresponding antiquarks partners in antiproton. This does not set any constraint on the quantum numbers of the final states enabling to reach all the charmonium states by the direct formation. On the other hand, in electron-positron annihilation, the direct creation of final charmonium states is constrained to the quantum numbers of the photon ($J^{PC} = 1^{--}$). Other states can be reached only indirectly by other mechanisms.

The first charmed baryon states were detected in 1975 in neutrino interactions [4]. Since then, many new excited charmed baryon states have been discovered by the CLEO, *BABAR*, and Belle facilities. However, the production and spectroscopy of the charmed baryons have not been explored in the same detail as the charmonium states, although they can provide similar information about the quark confinement mechanism. In fact, due to the presence of three quarks (two light and one heavy), the structure of the charmed baryon is more intriguing and complicated. In contrast to mesons, there can be more states as there are more possibilities of orbital excitations. The advantage of using antiprotons in the study of the charmed baryon is that in $p\bar{p}$ collisions the production of extra particles is not needed for charm conservation, which reduces the threshold energy as compared to, say, pp collisions.

The $\bar{P}ANDA$ ("antiproton annihilation at Darmstadt") experiment will use the antiproton beam from the Facility for Antiproton and Ion Research (FAIR) colliding with an internal proton target and a general purpose spectrom-

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eter to carry out a rich program on the the charm baryon and charmonium productions in proton-antiproton annihilation. The entire energy region below and above open charm threshold will be explored in these studies. Charmonium states above open charm threshold will generally be identified by means of their decays to $\bar{D}D$ systems, unless this is forbidden by some conservation rule. The beam momenta of antiprotons in $\bar{P}ANDA$ experiment will be well above the threshold (10.162 GeV/c) of the Λ_c charmed baryon production reaction $\bar{p}p \to \bar{\Lambda}_c^- \Lambda_c^+$ reaction, therefore significant yields of this reaction is expected at the $\bar{P}ANDA$ energies ($\sim$ 15 GeV).

The reliable estimation of the rates of $\bar{p}p \to \bar{D}^0 D^0$ and $\bar{p}p \to D^- D^+$ reactions (to be referred together as the $\bar{p}p \to \bar{D}D$ reaction) at the $\bar{P}ANDA$ energies is required for the accurate detection of the charmonium states above the $\bar{D}D$ threshold. In addition, it is also important for other studies such as the open charm spectroscopy, the search for charmed hybrids decaying to $\bar{D}D$, the investigation of the rare decays and of the charge conjugation-parity (CP) violation in the D meson sector. All these topics are the major components of the $\bar{P}ANDA$ Physics program [5]. The accurate knowledge of these reactions is also the primary requirement for investigating the creation of the exotic flavored nuclear systems like charmed hypernuclei [6] and charmed D-mesic nuclei [7]. Similarly for the planning of the charmed baryon production reaction, reliable theoretical estimates of the cross section of this reaction would be of crucial importance.

The production rates of reactions $\bar{p}p \to \bar{\Lambda}_c^- \Lambda_c^+$, $\bar{p}p \to \bar{D}^0 D^0$, and $\bar{p}p \to D^- D^+$ near $\bar{P}ANDA$ energies have been estimated by several authors using a variety of models. However, the magnitudes of the predicted cross sections are strongly model dependent – they differ from each other by several orders of magnitudes. Therefore, it is of great interest to the $\bar{P}ANDA$ experiment to determine reliably the rates of these reactions for beam momenta of around 15 GeV within a theory that is appropriate for this energy range.

In this talk, we discuss the results of our investigations for the cross sections of the charmed baryon production reaction $\bar{p}p \to \bar{\Lambda}_c^- \Lambda_c^+$, and charmed meson production reactions $\bar{p}p \to \bar{D}^0 D^0$, and $\bar{p}p \to D^- D^+$ within a single-channel effective Lagrangian model (see, e.g., Refs. [8–10]). The charmed baryon proceeds via the t-channel D^0 and D^{*0} meson-exchange diagrams while the charmed meson reactions are described as a sum of the t-channel Λ_c^+, Σ_c^+, Σ_c^{++} baryon-exchange diagrams and the s-channel excitation, propagation and decay into the $D\bar{D}$ channels of the $\Psi(3770)$ resonance. The t-channel part of the model is similar in both the baryon and meson production reactions. We shall discuss the results of our calculations in comparison to those of other authors and outline their reliability at $\bar{P}ANDA$ energies. We shall also discuss the role of the $\Psi(3770)$ resonance in the charmed meson production process.

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References

[1] T. Kawanai and S. Sasaki, arXiv:1503.05752 [hep-lat].

[2] J. Aubert *et al.*, Phys. Rev. Lett. **33**, 1404 (1974).

[3] J. Augustin *et al.*, Phys. Rev. Lett. **33**, 1406 (1974).

[4] E. Cazzoli *et al.*, Phys. Rev. Lett. **34**, 1125 (1975).

[5] W. Erni *et al.*, arXiv:0903.3905 [hep-ex].

[6] C. B. Dover and S. H. Kahana, Phys. Rev. Lett. **39**, 1506 (1977).

[7] C. Garcia-Recio, J. Nieves, L. L. Salcedo, and L. Tolos, Phys. Rev. C 85, 025203 (2012).

[8] R. Shyam, Phys. Rev. C **60**, 055213 (1999).

[9] R. Shyam and H. Lenske, Phys. Rev. D **90**, 014017 (2014).

[10] R. Shyam and H. Lenske, Phys. Rev. D (2015), to be published.