Open-charm physics: from $e^+e^-$ to $\bar{p}p$ machines

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Abstract. This report intends to summarize the most interesting experimental results in open-charm physics achieved by the past $e^+e^-$ experiments, and show some new theoretical developments, in particular for $D_s$ mesons, for the cross section calculations in $\bar{p}p$ annihilation processes. After the observation of the $D_s^+(2317)^+$, more than 10 years ago, still questions remain opened due to the lack of precision measurements. The measurement of the width of narrow states below the $D(\ast)K$ threshold in this respect is essential for a better understanding: a technique to measure that will be shown, and an overview on new future facilities where this measurement can be achieved will be given. In particular, we will focus on the role of the future PANDA experiment at FAIR, and the unique contribution of this project in the measurement of the $D(\ast)$ very narrow widths.

1. Introduction
Since 2003 unexpected observations and evidence of new resonant states questioned the validity of the Quark Potential Model (QPM), which well explains e.g. most of the $D_s$ spectrum, but not the mass shift of the $D_{s0}(2317)^+$ and the $D_{s1}(2460)^+$ from the theoretical prediction of Godfrey and Isgur [1]. The peculiar behaviour of these two states is actually not very understandable, because $D_s(\ast)$ mesons are binding states of a $c$-quark and a $s$-quark. The $s$-quark can be considered light enough to fit the QPM theoretical calculations, and effectively it was experimentally demonstrated so until the discovery of the $D_{s0}(2317)^+$ [2]. In the same year of the $D_{s0}(2317)^+$ discovery a new state decaying to $J/\psi\pi^+\pi^-$, the so-called $X(3872)$ [3] was announced. This was also a puzzling observation, unexpected and incredibly narrow. After 14 years tens of these new states populate the charm- and charmonium(like)- spectrum. The measurement of their mass, width, and decay products is essential to draw a pattern in order to understand their nature, especially since the charged $Z$ charmonium states have been announced. A great contribution was given by the past experiments BaBar and Belle, and recently from BES III and LHCb. However, still questions remain unanswered due to limitations in mass resolution and photon detection, which nowadays do not allow to discriminate among the theoretical models developed after the discovery of those states.

2. Cross section predictions
The study of charm physics is interesting from both points of view, weak and strong interactions. This short report concentrates on the study and development of the latter.

First Belle [4] then BaBar [5] have studied the cross sections of the processes $e^+e^- \rightarrow D(\ast)\bar{D}(\ast)$ via ISR, resulting in the same conclusion: for energy values in the center-of-mass region $\sqrt{s} > 4.2$
GeV the cross section is lower than 4 nb, and slightly decreases with increasing $\sqrt{s}$. BaBar also performed the the cross section measurements of the $e^+e^- \rightarrow D_s^+(s)D_s^{(*)}$ processes via ISR [6], ending with measurements lower than 1 nb. No other measurements are published. One could in principle ask the question what the value of the equivalent cross sections in $\bar{p}p$ annihilation is, and if this measurement could add information for better understanding the $D(s)^*$ and $D_s^{(*)}$ spectrum.

Cross section predictions in $\bar{p}p$ annihilations for the $cs$ spectrum are difficult due to the presence of the $s$-quark, because it is definitively lighter than the $c$-quark, but not light enough to use the same approximations when developing theoretical calculations for heavy-light systems: divergences, which are difficult to cure, occur. As a general remark, the cross section $\sigma(\bar{p}p) \rightarrow DD$ is expected to be lower than 100 nb: this conclusion rises from the old studies of $\bar{p}p \rightarrow$ charged mesons [7]. However, the most quoted theoretical papers to predict $\bar{p}p$ annihilation into D mesons are not in good agreement with each other: Braaten and Artoisenet [8] make use of NLO and LO approaches, and rate the cross section in the range $0.002$-$0.09$ nb at $\sqrt{s} \sim 4$ GeV in inclusive charm production in $\bar{p}p$ collisions, and in the range of $10$-$100$ nb at $\sqrt{s} \sim 6$ GeV in the same processes; Khodjamirian, Klein, Mannel and Wang [9] range $\sigma(\bar{p}p \rightarrow D^+D^-)$ in the interval $10^{-8}$-$10^{-2}$ nb at $p_{lab}=6$ GeV/$c$, and it decreases smoothly up to $p_{lab}=20$ GeV/$c$. However, they show a huge gap between the prediction for $pp \rightarrow D^+D^-$ and $\bar{p}p \rightarrow D^0\bar{D}^0$ cross sections, in favor of the latter. Recent theoretical developments by Heidenbauer and Krein [10] have come to a different conclusion: using the SU(4) symmetry and then assuming that all coupling constants are fixed, and adding the neutron in the baryon loop exchange, they quote the $\bar{p}p \rightarrow D^0\bar{D}^0$ and $\bar{p}p \rightarrow D_s^+D_s^-$ cross sections in a similar range, e.g. $10^{-3}$ nb at $p_{lab}=6.4$ GeV/$c$, and $10^{-1}$ nb at $p_{lab}=7.5$ GeV/$c$. In the same paper for the first time a prediction of the $\bar{p}p \rightarrow D_s^+D_s^-$ cross section is given: depending on the model, quark model or baryon exchange approach, a range of $10$-$100$ nb can be extrapolated for the cross section prediction of the $\bar{p}p \rightarrow D_s^+D_s^-$ process. Nothing is calculated for $\bar{p}p \rightarrow$ excited $D_s$ mesons, for which even with this approach no predictions can be made.

In summary, from a theoretical point of view still no predictions exist for the excited $D_s$ mesons in $\bar{p}p$ annihilation, but with the approach followed in Ref. [10] at least the cross section for the ground $D_s$ states is provided. What is needed then is to perform measurements using a $\bar{p}p$ experiment that can cover the $p_{lab}$ range of 6-10 GeV/$c$.

3. The PANDA experiment at FAIR

The PANDA (antiProtons ANihilation at DArmstadt) [11] experiment at the Facility for Antiprotons and Ion Research (FAIR) is a future project that is going to be realized in different phases, depending on the availability of detectors and infrastructure: Phase 0 starting in 2018 with the commissioning of detector components; Phase I, the start-up phase, with a limited detector setup; and Phases II-III utilizing the full detector setup with varying luminosities.

The scheme of the detector with full setup is shown in Fig. 1. The PANDA detector will be a $4\pi$ coverage detector, operating with an antiproton beam with momentum of up to p=15 GeV/$c$, and a fixed target. It will be realized in two main parts: a central spectrometer inside a solenoidal magnetic field (2 T), and a dipole spectrometer (bendig power: 2 T·m). Due to the high boost ($\beta_{cm} \geq 0.8$) many tracks and photons will be in the forward detector. Background and signal will have the same signature, therefore a complete real-time event reconstruction needs to be performed. The interaction rate will be enormous, up to 20 MHz. We expect a small signal over background (S/B) ratio in our analyses, typically between $10^{-7}$ and $10^{-8}$, so proper techniques to reject the background, online and offline, have to be developed. The PANDA detector will have an excellent photon reconstruction, a good tracking system, and a high PID (particle identification) separation power.

The PANDA physics program is wide and ambitious. In particular, the measurement of the
open-charm cross sections can start during the first phase of data taking. The measurement of the width of narrow states such as the \( D_{s0}^*(2317)^+ \), which represents one of the most ambitious challenges of the PANDA physics program, can be performed only with the complete setup of the experiment: due to the expected low values of the \( D_{s0}^*(2317)^+ \) cross sections, high statistics is needed.

4. Challenges in \( D_s \) meson spectroscopy

The technique to measure the width of narrow states in PANDA is the energy scan. This is a known technique to observe resonant states in \( \bar{p}p \) annihilation processes. In any case, before performing the threshold energy scan of the \( \bar{p}p \to D_s^- D_{s0}^*(2317)^+ \) process to measure the width of the \( D_{s0}^*(2317)^+ \), the measurement of the cross section is needed and it is prioritized. This would give a hint on how many events per day we can collect for each energy-scan point, and how long this experiment should run.

In order to perform measurements in the open-charm sector, we need a good tracking system, and an excellent photon reconstruction. Our Monte Carlo (MC) simulations suggest that the photon energy resolution is below 2% at \( E = 1 \) GeV [12], and the photon energy detection threshold is \( \leq 30 \) MeV [13].

Among all channels of interest to which PANDA can make an original contribution, we point here the attention of the reader to the \( \bar{p}p \to D_s^- D_{s0}^*(2317)^+ \) process, which is a channel of multiple interests:

- cross section measurement;
- width measurement;
- chiral symmetry breaking studies.
We need to run the antiproton beam in PANDA at $p_{lab} \geq 8.802$ GeV/c to study such a process: this is the threshold value to generate the $D_s^-D_{s0}^*(2317)^+$ pair. We need to produce always a couple of $D_s$ mesons in such a process, because they are charged particles and we want to analyze the process through $\bar{p}p$ annihilation. Then additional values should be collected below and above that value, to reconstruct the excitation function of the cross section of the process under investigation. A proposal to collect 15 energy-scan values is planned.

The measurement of the $D_{s0}^*(2317)^+$ width is crucial to understand the nature of this resonant state. Several theoretical papers have been published, interpreting the $D_{s0}^*(2317)^+$ as a pure $cs$ meson, if its width will be in the order of 10 keV [14]; tetraquark, if the width is in the order of 10-100 keV [15]; molecular state if the width will be $\sim 133$ keV [16].

The measurement of the $D_{s0}^*$ width will be performed by scanning the energy of the $D_s^-D_{s0}^*$ system in 100-keV-steps. The mathematical expression of the excitation function of the cross section of such a process is:

$$\sigma(s) = \frac{|M|^2}{64 \pi p_{lab}^2} \Phi(E),$$

where $\Phi(E)$ is the spectral function, that assumes a very easy expression under the condition that $\sqrt{s} - M_{D_s} - M_{D_{s0}^*(2317)} / \Gamma(D_{s0}^*(2317)) \gg 1$. In this case, the excitation function of the cross section of the mentioned process depends only on the $D_{s0}^*(2317)$ width, the mass of the 2 mesons, and the momentum in the $D_{s0}^*$ rest frame. By scanning the energy of the $D_s^-D_{s0}^*$ system in 15 100-keV-steps, it is possible to draw the plot shown in Fig. 2. Here different width input values deliver different shapes of the excitation function of the cross section. The ability of PANDA to perform this study with precision, and minimizing the error bars inevitably affecting every measurement, point by point, should make it possible to distinguish among different theoretical hypotheses.

Table 1 summarizes the expected number of produced events per day under some cross section input values, for the initial and the final setups of the experiment.

![Figure 2. Excitation function of the cross section for the $\bar{p}p \rightarrow D_s^-D_{s0}^*(2317)^+$ process. Different color lines correspond to different input values of the $D_{s0}^*(2317)^+$ width [17].](image)

If the $D_{s0}^*(2317)^+$ width is measured in the order of 100 keV, then the hypothesis of it being a molecular state will be confirmed, and all other hypotheses will be ruled out. If indeed PANDA will not succeed to measure the $D_{s0}^*(2317)^+$ width, the most precise upper limit to the $D_{s0}^*(2317)^+$ width will be fixed: this would imply that the hypothesis of the $D_{s0}^*(2317)^+$ being
Table 1. Summary of the produced events per day for the $\bar{p}p \rightarrow D_s^- D_{s0}^*(2317)^+$ process. The average luminosity for the startup mode corresponds to $10^{31} \text{cm}^{-2} \text{s}^{-1}$; the average luminosity for the final setup in high luminosity mode corresponds to $10^{32} \text{cm}^{-2} \text{s}^{-1}$.

| Input $\sigma$ (nb) | Produced events per day (startup mode) | Produced events per day (full luminosity) |
|--------------------|----------------------------------------|--------------------------------------------|
| 20                 | 17280                                  | 172800                                     |
| 10                 | 8640                                   | 86400                                      |
| 5                  | 4320                                   | 43200                                      |
| 2                  | 1728                                   | 17280                                      |
| 1                  | 864                                    | 8640                                       |

a molecular state can be rejected. The known upper limit from PDG [18] to the $D_{s0}^*(2317)^+$ width is 3.8 MeV.

5. Summary
In summary, the study of charm physics is important because nowadays open-questions remain, which the currently running projects cannot address. Among these, the measurement of the $D_{s0}^*(2317)^+$ width represents a challenge, due to the high background level compared to the signal expectation, and it is one of the highlights of the PANDA physics program. The unknown cross section of the $\bar{p}p \rightarrow D_s^- D_{s0}^*(2317)^+$ process does not allow to make clear predictions: data are needed. It will be not easy to perform such a measurement, but the high detector resolution of PANDA allows to perform the energy scan in $\sim$100-keV-steps. Full simulations for the decay process under investigation are ongoing [19], and preliminary results are promising.

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