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Threshold scan at $\overline{\text{P}}$ANDA

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The future experiment $\overline{\text{P}}$ANDA@FAIR is a fixed-target $\bar{p}p$ experiment that will run in the antiproton momentum range [1.5-15.0] GeV/c, and is supposed to reach a peak luminosity up to $2{\cdot}10^{31}$ cm^{-2} s^{-1} in the first phase of data taking. This will allow to perform analyses of a number of reactions which are suppressed or forbidden at running experiments, especially in the sector of charm and charmonium physics. Investigating narrow resonances, measure their width and understand their properties is the core of the $\overline{\text{P}}$ANDA physics program in the *day-one* experiment. This contribution reports about the feasibility studies to measure the width of very narrow states by performing a threshold scan. The case of the $D^*_{s0}(2317)^+$ will be discussed with new theoretical developments to evaluate the cross section and the rate for the process $\bar{p}p \to D^-_s D^*_{s0}(2317)^+$, as an original contribution to the $\overline{\text{P}}$ANDA physics program. Eventually new resonances with $\bar{c}c\bar{s}s$ quark content could be investigated in the $D^-_s D^*_{s0}(2317)^+$ invariant mass system. We recall that recently the LHCb experiment published about four resonances with the above mentioned quark content in the $J/\psi\phi$ invariant mass system through B decays, only. Therefore the hereby presented study might be of high interest from experimental as well as theoretical point of view, and offers a complementary search in a different reaction mechanism.

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1. Introduction

In the study of fundamental interactions in particle physics, one of the important topics is the QCD (Quantum Chromo Dynamics), for which several phenomena are non-understood yet. Understanding QCD means, among other things, to understand confinement and chiral symmetry breaking, that can be done -from an experimental point of view- by measuring observables: the precise measurement of masses and widths, search for new decay modes, the angular analysis to determine the parity of resonant states in different reaction mechanisms (if possible) can help to understand potentials and more general the dynamics of hadrons.

In the year 2003 the so-called $D^*_{s0}(2317)^+$ was observed[1] for the first time by the BaBar experiment [1], and followed by confirmation from several other experiments [2, 3, 4, 5, 6]. The mass is nowadays measured with precision, and equal to (2317.7 ± 0.6) MeV/c^2 [7], but its width remains unknown ($\Gamma <$ 3.8 MeV at 95% confidence level). The narrow $D^*_{s0}(2317)^+ \to D_s^+\pi^0$ resonance at 2317 MeV/c^2 is naturally interpreted as a P-wave excitation of the cs-system. The observation of a nearby and narrow $D_s^{*+}\pi^0$ resonance, known as the $D_{s1}(2460)^+$, supports this view, since the mass difference of the two observed states is consistent with the expected hyperfine splitting for a P-wave doublet with total light-quark angular momentum j=1/2. The observed masses are, however, 160 MeV/c^2 and 120 MeV/c^2 lower, respectively, than predicted by static quark potential models [8, 9], and similar to those of the cu j = 1/2 doublet states. This has given rise to speculation that the $D_s^{(*)+}\pi^0$ resonances may be exotic mesons, not pure cs-states. Measurements of the $D_{sJ}^{(*)}$ quantum numbers and branching ratios play then an important role, as well as the measurement of the width of these narrow states, to determine their nature and discriminate among theoretical models. Up to now, only width upper limits (ULs) have been measured: 3.8 MeV and 3.5 MeV, for the $D^*_{s0}(2317)^+$ and the $D_{s1}(2460)^+$, respectively [7]. Indeed predictions for the width well below 1 MeV have been formulated, as summarized in Table 1.

Reference	$D^*_{s0}(2317)^+$ width predictions (keV)	Interpretation
[10]	6 ± 2	pure cs-state
[11]	7 ± 1	pure cs-state
[12]	10	pure cs-state
[13]	$10-100$	tetraquark
[14]	79.3 ± 39.6	DK molecule
[15]	140	Dynamically generated resonance
[16, 17]	133 ± 22	DK molecule

Table 1: Summary of theoretical predictions for the $D^*_{s0}(2317)^+$, depending on the width value.

The measured mass value being lower than predicted by Godfrey and Isgur [8], and later on by Di Pierro and Eitchen [9], is indeed very surprising, because heavy-light systems have been generally and qualitatively described very accurately by potential models in non-relativistic approach. Experimentally it was proven this is valid for all known mesons of the cs-spectrum, with only three exceptions: the $D^*_{s0}(2317)^+$, the $D_{s1}(2460)^+$ and the $D_{s1}(2860)^+$.

[1]The charged conjugate is meant throughout all text, unless stated otherwise.

We propose to perform the measurement of the narrow $D_{s0}^{*}(2317)^{+}$ width at the new generation experiment $\overline{\text{P}}$ANDA, that will be located at the HESR at FAIR [18] (High Energy Storage Ring at the Facility for Antiproton and Ion Research). $\overline{\text{P}}$ANDA is an approved and currently under construction experiment, aiming to perform a wide physics program and reach a mass resolution 20 times superior to its predecessors that could allow to perform the measurement of the $D_{s0}^{*}(2317)^{+}$ width with a threshold scan for the formation reaction with a cooled antiproton beam. The past experiments where the $D_{s0}^{*}(2317)^{+}$ resonance was observed could reach a mass resolution of about 2 MeV/c^2 only, while for the measurement of the $D_{s0}^{*}(2317)^{+}$, according to Table 1, one needs to reach a resolution even lower than 100 keV/c^2. The description of the $\overline{\text{P}}$ANDA detector and the $\overline{\text{P}}$ANDA physics program is done elsewhere [19].

2. Analysis strategy

The $D_{s0}^{*}(2317)^{+}$ is a charge particle, therefore cannot be produced alone in $\bar{p}p$ annihilation, but formed in pair. The possible reaction meachanism to analyze is: $\bar{p}p \to D_s^- D_{s0}^{*}(2317)^{+}$, with $D_{s0}^{*}(2317)^{+} \to D_s^+ \pi^0$, $D_s^{\pm} \to K^+ K^- \pi^{\pm}$ and $\pi^0 \to \gamma\gamma$. The final interaction requires then the reconstruction of 6 charged tracks and 2 neutral particles. The excellent performance of the $\overline{\text{P}}$ANDA calorimeter, together with the good tracking system, will allow to perform this analysis with the required precision: we plan to reconstruct photons with momentum p>30 MeV/c, and we are able to reconstruct low momentum tracks with high reconstruction efficiency [20]. The mass resolution for the reconstruction of the $D_s^{\pm} \to K^+ K^- \pi^{\pm}$ chain is of about 16 MeV/c^2 [21], and with a fit mass constraint we can lower that to 11 MeV/c^2. However, to measure the width of the $D_{s0}^{*}(2317)^{+}$ implies a threshold scan in 100-keV-steps, that the $\overline{\text{P}}$ANDA experiment can effort thanks to the good HESR momentum resolution, *e.g.* Δp/p$\leq 10^{-4}$. The idea is to scan the invariant mass system of $D_s^- D_{s0}^{*}(2317)^{+}$ in 15 points, 7 collected below and 7 collected above the threshold, and one exactly at the nominal threshold of 4285.98 MeV/c^2, to reproduce the excitation function of the cross section as shown in Fig. 1. In that figure it is possible to see that the shape of the excitation function of the cross section, as function of the invariant mass system of $D_s^- D_{s0}^{*}(2317)^{+}$, varies with the width value assigned as input to the $D_{s0}^{*}(2317)^{+}$ in the reported pseudo-Monte Carlo experiment. The formula of the excitation function of the cross section is explicitly given below:

$$\sigma(s) = \frac{|\mathscr{M}|^2}{64 \cdot \pi \cdot p_1^* \cdot s} \Phi(E) \tag{2.1}$$

where s = square of the energy in the center-of-mass of the system; p_1^* = momentum of the antiproton beam; $\mathscr{M}$ = matrix element; $\Phi(E)$ = spectral function: it depends on the mass and the width of the resonant state that we want to measure.

$$\Phi(E) = \frac{1}{\pi} \sqrt{\left(\frac{MM^*\Gamma^*}{M+M^*}\right)} \cdot \int_{-\infty}^{E_0} d\delta \frac{1}{\delta^2+1} \sqrt{E_0 - \delta} \tag{2.2}$$

where $E_0 = 2(\frac{\sqrt{s}-M-M^*}{\Gamma^*})$, with $M = M_{D_s^-}$, $M^* = M_{D_{s0}^*(2317)^+}$ and Γ^* = width of the $D_{s0}^{*}(2317)^{+}$ [23].

In the above equation the dependence of the cross section from the $D_{s0}^{*}(2317)^{+}$ width is clearly shown: it will be extracted as a fit parameter, and the comparison with the theoretical expectations shown in Fig. 1 will allow to discriminate among the theoretical models reported in Table 1.

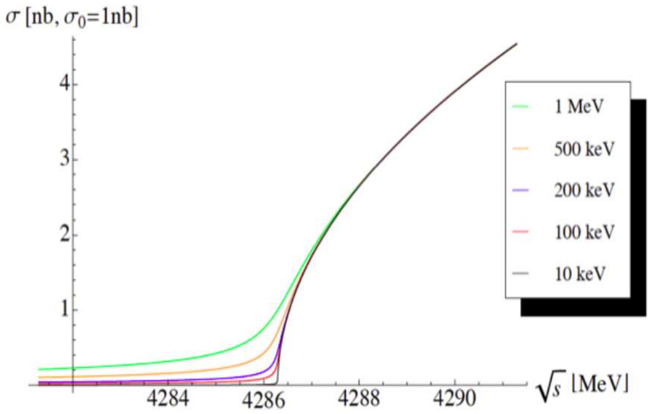

Figure 1: Excitation function of the cross section for $\bar{p}p \to D_s^- D_{s0}^*(2317)^+$.

3. Cross section evaluation in the open-charm sector

Very little is known about cross sections in open charm, expecially when excited cs states are involved. Heavy-light quark systems are difficult to treat from theoretical point of view, as the non-perturbative calculations not always deliver correct results. In fact, due to the peculiar behaviour of the s quark, that is not heavy but also not a light quark, the mass of the $D_{s0}^*(2317)^+$ was measured well below the predicted value. This brings an issue also in the theoretical evaluation of the cross section. In $\overline{\text{P}}$ANDA we plan to perform also a semi-inclusive analysis, *e.g.* we tag the prompt $D_s^- \to K^+K^-\pi^-$ and reconstruct the $D_{s0}^*(2317)^+$ on the D_s^- recoil for a better $D_s^- D_{s0}^*(2317)^+$ mass resolution compared to the exclusive process, and enlarge the statistics. To estimate the cross section of the mentioned semi-inclusive process is extremely hard, since the $\overline{\text{P}}$ANDA energy is close to the $\bar{c}c$ threshold, so perturbative calculations will not work out [24]. Furthermore, also higher excited D_s states can be produced which cascade down into the states that we plan to investigate. To our knowledge on the production of exclusive charm, the perturbative calculations always seem to underestimate the cross sections by large factors. So, if one takes the fully inclusive charm production (as calculated *e.g.* by Braaten [25]), one can predict an UL of the expected cross section. On the other hand, these calculations are perturbative, so they will probably underestimate the real cross section for $\bar{p}p \to$ open charm in the $\overline{\text{P}}$ANDA energy region. Some theoretical predictions performed by Haidenbauer and Krein [26] assume as valid the SU(4) symmetry, in a calculation performed following two different approaches, baryon exchange and quark model. However, these calculations apply only to ground D_s states, not to the excited $D_s^{(*)}\pi^0$ resonances. If one is looking into a semi-inclusive process, the c quark has to hadronize into the $D_{s0}^*(2317)^+$ state. Still nothing is known about fragmentation functions for $D_s^{(*)}\pi^0$ states, which anyway would only hold for a perturbative situation at much higher energies. Nevertheless, in general the semi-inclusive cross section has to be smaller than the fully inclusive.

What is needed to clarify the situation is to analyze data; therefore we are looking forward for $\overline{\text{P}}$ANDA starting to collect data, and perform first of all the measurement of the cross section of the process under investigation, then the threshold scan to measure the width of the $D_{s0}^*(2317)^+$.

4. Extrapolation and comparison

Table 2 reports the expected number of produced events per day for the proposed analysis, depending on different input values of the signal cross section.

Input $\sigma(s)$ (nb)	Produced events per day ($\overline{\text{P}}$ANDA start-up)	Produced events pe day ($\overline{\text{P}}$ANDA full luminosity)
20	17280	172800
10	8640	86400
5	4320	43200
2	1728	17280
1	864	8640

Table 2: Summary of the produced $D^*_{s0}(2317)^+$, depending on the assumption on the cross section of the process $\bar{p}p \to D_s^- D^*_{s0}(2317)^+$. The expected maximum luminosity value in the start-up mode is 10^{31} cm^{-2} s^{-1}; this number will rise to a factor 10 higher in the full luminosity setup of the experiment.

The measurement of the cross section could be performed even in the day-one experiment, assuming a reconstruction efficiency of a couple of points per cent, which results from our preliminary PandaRoot full simulations [22]. For comparison, at the B factories BaBar and Belle the $D^*_{s0}(2317)^+$ was reconstructed with roughly 10% efficiency in inclusive continuum production, and with $\leq 10^{-4}$ reconstruction efficiency through B decays. We can expect that the future experiment Belle II will reconstruct roughly 44000 $D^*_{s0}(2317)^+$ when it will reach 50 ab^{-1} integrated luminosity, by extrapolating the results obtained by the previous Belle experiment at KEK [2, 3]. However, a 100-keV-step scan could be performed at the $\overline{\text{P}}$ANDA experiment, only.

The disadvantage in analyzing the semi-inclusive $\bar{p}p \to D_s^- D^*_{s0}(2317)^+$ process at $\overline{\text{P}}$ANDA is the high background cross section, compared to what one can expect for the signal. For this purpose, a neural network background study is ongoing. The advantage in analyzing the semi-inclusive $\bar{p}p \to D_s^- D^*_{s0}(2317)^+$ process at $\overline{\text{P}}$ANDA is indeed to have a higher statistics compared to an exclusive analysis approach.

The analysis of the $D^*_{s0}(2317)^+$ offers also other interesting opportunities:

- to search for exotic states in the invariant mass system of $D_s^- D^*_{s0}(2317)^+$, which was not performed until now due to the low efficiency in the D_s reconstruction: it makes this analysis hard to perform;
- chiral symmetry breaking studies. We recall that the mass difference ($m_{D^*_{s0}(2317)^+} - m_{D_s^+}$) was already measured, and found equal to (349.4 ± 0.6) [7].

5. Summary

In summary, the $\overline{\text{P}}$ANDA experiment will be realized at FAIR 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. One of the most important analyses of the $\overline{\text{P}}$ANDA physics program is the measurement of the narrow width of the $D^*_{s0}(2317)^+$. This analysis could be performed in a semi-inclusive approach, scanning the invariant mass system of the $D^-_s D^*_{s0}(2317)^+$ in 100 keV-steps. The role of the HESR is essential in performing this analysis, and will make it feasible. If the $D^*_{s0}(2317)^+$ is a molecular state, $\overline{\text{P}}$ANDA will allow the first and absolute measurement of its width with unprecedented precision. Cross section evaluations are difficult in the sector of open-charm physics, due to the lack of experimental inputs, and consequently theoretical predictions. Full simulations with PandaRoot are right now ongoing.

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