New Spectroscopy with $\overline{\text{P}}$ANDA at FAIR: X, Y, Z and the F-wave Charmonium States.

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Abstract. Charm and charmonium physics have gained renewed interest in the past decade. Recent spectroscopic observations strongly motivate these studies. Among the several possible reactions, measurements in proton-antiproton annihilation play an important role, complementary to the studies performed at B-factories. The fixed target $\overline{\text{P}}$ANDA experiment at FAIR (Darmstadt, Germany) will investigate fundamental questions of hadron and nuclear physics in the interactions of antiprotons with nucleons and nuclei. With reaction rates as large as 2×10^7 interactions/s, and a mass resolution 20 times better as compared with the most recent B-factories, $\overline{\text{P}}$ANDA is in a privileged position to successfully perform the measurement of the width of narrow states, such as the $X(3872)$. $\overline{\text{P}}$ANDA will investigate also high spin particles, whose observation was forbidden at B-factories, i.e. F-wave charmonium states. In this report extrapolations on cross sections and rates with $\overline{\text{P}}$ANDA are given.

INTRODUCTION

In the past decade many new, narrow states have been observed in the charmonium and bottomonium mass regions, which do not fit into a spectroscopical scheme as predicted by a static quark-antiquark potential model [1].

The $X(3872)$ [2, 3, 4, 5], for example, is found very narrow and close to the DD^* threshold. Recently the quantum numbers have been determined to $J^{PC} = 1^{++}$ by LHCb [6]. However, its nature is not understood, yet. The $Y(4260)$ [7, 8, 9] is found far above the open-charm thresholds; however no decay into $D^{(*)}\overline{D^{(*)}}$ has been observed so far. Therefore it is being discussed e.g. as a possible hybrid with gluonic excitation. Z states have raised attention after the discovery of the $Z(4430)$ [10, 11], because many of those Z states are charged, which is in contradiction to conventional charmonium, inevitably being neutral. In the past 2 years several resonant structures, namely the $Z_c(3900)$ [12, 13], the $Z_c(4020)$ [14], the $Z_c(3885)$ [15], and the $Z_c(4025)$ [16], have been observed. Their nature is still unclear.

The transition $Y(4260) \rightarrow Z(3900)^-\pi^+$ has been seen by BES III [17]; the transition $Y(4260) \rightarrow X(3872)\gamma$ has also been seen [18]. But no experiment until now looked for the transition $X \rightarrow Z$, or vice versa. Some Z states are observed decaying to DD^* or $\overline{D^*}D^*$. The mass values of the $Z_c(3885)$, the $Z_c(3900)$, and the $Z_c(4020)$, published by BESIII, are close to the DD^* and $\overline{D^*}D^*$ thresholds, respectively. Assuming that the Z states contain S-wave DD^* and $\overline{D^*}D^*$ components, the spin parity J^P of the $Z_c(3885)$ and the $Z_c(3900)$ would be $J^P= 1^+$, and the spin parity of the $Z_c(4020)$ is expected to be $J^P=0^+$, 1^+, or 2^+. The former is confirmed by BESIII experimental data. One can expect also similar S-wave resonances in the $\bar{D}D$ system, with $J^P= 0^+$ (C=+1 for the neutral state), and mass values about 3730 MeV/c^2, which are not observed yet.

In this context, the contribution of a $\bar{p}p$ machine has to be considered as essential, because it can either confirm the above BES III measurements, and look for the non-observed 0^+ Z states at the $\bar{D}D$ threshold, as $\bar{p}p$ annihilation is a gluon rich process with direct access to various quantum numbers in production processes. In addition, the possibility of F-wave charmonium state search has been explored, as a test of flavor independence to understand the quark-antiquark potential.

Estimates for the $X(3872)$ at $\overline{\text{P}}$ANDA.

The future $\overline{\text{P}}$ANDA experiment at FAIR (Facility for Antiproton and Ion Research) is well suited for charmonium studies, thanks to the high capability rate and the excellent mass resolution, that allows high precision measurements and energy scan. The experiment setup is described elsewhere [19].

One of the most striking advantages of the $\overline{\text{P}}$ANDA experiment is the opportunity to search for direct production of exotic resonant states with various quantum numbers, including charged ones in $\bar{p}d$ collisions. In e^+e^- experiments only neutral $J^{PC} = 1^{--}$ resonances can be directly produced, and production of exotic charmed states through other mechanisms is suppressed.

Using the detailed balance method, we can evaluate the cross section as:

$$\sigma[\bar{p}p \rightarrow R] \cdot BR(R \rightarrow f) = \frac{(2J + 1) \cdot 4\pi}{s - 4m_p^2} \cdot \frac{BR(R \rightarrow \bar{p}p) \cdot BR(R \rightarrow f) \cdot \Gamma_R^2}{4(\sqrt{s} - m_R)^2 + \Gamma_R^2} \quad (1)$$

where f is the final state of the decay channel, Γ is the total width of a resonance R, and $\sqrt{s}$ the center of mass energy. For example, in order to evaluate the cross section of the process $\bar{p}p \rightarrow X(3872)$, we make use of the Equation (1), and obtain:

$$\sigma[\bar{p}p \rightarrow X(3872)] \cdot BR(X(3872) \rightarrow f) = \frac{3 \cdot 4\pi}{s - 4m_p^2} \cdot \frac{BR(X(3872) \rightarrow \bar{p}p) \cdot BR(X(3872) \rightarrow f) \cdot \Gamma_{X(3872)}^2}{4(\sqrt{s} - m_{X(3872)})^2 + \Gamma_{X(3872)}^2}. \quad (2)$$

We know that the spin parity of the $X(3872)$ is $J^P = 1^+$. We assume here a non-polarized incident beam. Down below we will use the decay channel $J/\psi\pi^+\pi^-$ as f for the case of the $X(3872)$. If we run at $\sqrt{s} = m_{X(3872)} = 3.872$ GeV/c^2 the Equation (2) simplifies: $\sigma[\bar{p}p \rightarrow X(3872)] = \frac{3 \cdot 4\pi}{m_{X(3872)}^2 - 4m_p^2} \cdot BR(X(3872) \rightarrow \bar{p}p)$. Here we assume $c = \hbar = 1$.

The $BR((X(3872) \rightarrow \bar{p}p)$, then, enters the formula of Equation (2). We estimate it from the available experimental measurements in the PDG [20], and those published by the LHCb experiment [21]. The combination of both leads to an upper limit at 95% confidence level (c.l.): $\sigma(\bar{p}p \rightarrow X(3872)) < (68 \pm 0.4)$ nb. In agreement with theoretical predictions [22], a reasonable number for the upper limit of the cross section $\sigma(\bar{p}p \rightarrow X(3872)) = 50$ nb. Therefore, in $\overline{\text{P}}$ANDA we use to evaluate the expected $X(3872)$ yield by using the above cross section estimate. This value should be interpreted as an upper limit. A lower limit estimate to the $X(3872)$ cross section cannot be quoted yet, simply because its very narrow width leads to unreasonable lower limits, by using standard methods for cross section evaluations.

$\overline{\text{P}}$ANDA could start in different operation modes, involving different antiproton beam resolution and luminosity values. Assuming the $X(3872)$ cross section in $\bar{p}p$ annihilation equal to 50 nb [22, 23], we are expected to produce 432000 $X(3872)$ per day in high luminosity mode (average luminosity $\mathcal{L} = 10^{32}$ cm^{-2} s^{-1}), and 43200 $X(3872)$ per day in high resolution mode (average luminosity $\mathcal{L} = 10^{31}$ cm^{-2} s^{-1}). Thus, $\overline{\text{P}}$ANDA can be considered as a "mini-$X(3872)$-factory". In the latter situation, the mass scan in 100-keV-steps, that is needed to measure the $X(3872)$ width, can be performed in about 3 weeks, collecting 15 points above and below the mass threshold, as detailed explained in Ref. [24]. In high resolution mode, $\overline{\text{P}}$ANDA is designed to have $\Delta p/p = 5 \cdot 10^{-5}$.

Estimates for the $Y(4260)$ at $\overline{\text{P}}$ANDA.

We calculate the number of produced $Y(4260)$ by multiplying the expected luminosity and the cross section of the process $\bar{p}p \rightarrow Y(4260)$. We assume $BR(Y(4260) \rightarrow J/\psi\pi^+\pi^-) = 100\%$, for four reasons:

- the decay $Y(4260) \rightarrow J/\psi\pi^+\pi^-$ was the discovery mode [7];
- for all known $Y(4260)$ decay channels, the PDG [20] quotes "seen" with no numbers reported;
- all searches for decays to open charm performed at B factories, in ISR and B decay modes, lead to upper limits only. In the PDG [20], these upper limits are all normalized to the $BR(Y(4260) \rightarrow J/\psi\pi^+\pi^-)$ [25, 26, 27, 28, 29, 30, 31, 32];
- recently, the BESIII experiment published the observation of the transition $Y(4260) \rightarrow \gamma X(3872)$ [18], from which it can be concluded that the $BR(Y(4260) \rightarrow \gamma X(3872))$, $X(3872) \rightarrow J/\psi\pi^+\pi^-$, contributes in negligible way to the total $BR(Y(4260))$, i.e. $\leq 0.5\%$ only.

The cross section of the process $\bar{p}p \to Y(4260)$ can be estimated using detailed balance (Equation (1)). However, if the poorly known upper limit $BR(Y(4260) \to \bar{p}p)/BR(Y(4260) \to J/\psi\pi^+\pi^-) <0.13$ at 90% c.l. [33] is taken as estimate and inserted into Equation (1), it leads to an unrealistically cross section estimate of 4370 nb.

If the BR of a resonant state, decaying to $\bar{p}p$, is known, we can directly apply the detailed balance method to evaluate the cross section. However, if this BR is not known, at first we use the ansatz that partial width is identical for states R_1, R_2 of the same quantum number [19].

$$BR(R_1 \to p\overline{p}) = BR(R_2 \to p\overline{p}) \cdot \frac{\Gamma_{total}(R_2)}{\Gamma_{total}(R_1)}. \tag{3}$$

This method assumes that the partial widths $\Gamma(R \to \bar{p}p)$ of all charmonium states are identical, where R refers to the state. Although we might have indication that the $Y(4260)$ is not a charmonium state, no model exists to evaluate the cross section for exotic states. In absence of any explanation of the $Y(4260)$ nature, thus we perform our calculation under the naive assumption that it is a charmonium state. As a reference state for the $Y(4260)$ estimates, we choose the $\psi(3770)$, for which the following numbers have been recently measured [35]: $BR(\psi(3770) \to \bar{p}p) = (7.1^{+8.6}_{-2.9}) \cdot 10^{-6}$, and $\sigma(\bar{p}p \to \psi(3770)) = (9.8^{+11.8}_{-3.9})$ nb. We start our calculation from Equation (3), using $\psi(3770)$ as a reference, and obtain:

$$BR(Y(4260) \to p\overline{p}) = BR(\psi(3770) \to p\overline{p}) \cdot \frac{\Gamma_{total}(\psi(3770))}{\Gamma_{total}(Y(4260))}. \tag{4}$$

We can write again Equation (4), using the detailed balance principle, as:

$$\sigma(p\overline{p} \to Y(4260)) = \sigma(p\overline{p} \to \psi(3770)) \cdot \frac{\Gamma_{total}(\psi(3770))}{\Gamma_{total}(Y(4260))} = 9.8 \ nb \cdot \frac{27.2 \ MeV}{102 \ MeV} = 2.2 \ nb. \tag{5}$$

We assume the cross section of Equation (5) as an upper limit. In order to estimate a lower limit for the cross section $\bar{p}p \to Y(4260)$, we use the assumption that the annihilation part, which manifests in the decay into e^+e^- and the decay into $\bar{p}p$, are identical:

$$\sigma(p\overline{p} \to Y(4260)) = 2.2 \ nb \cdot \frac{\Gamma_{ee}(Y(4260))}{\Gamma_{ee}(\psi(3770))} = 2.2 \ nb \cdot \frac{\Gamma_{ee}(Y(4260))}{BR(\psi(3770) \to e^+e^-) \cdot \Gamma_{total}(\psi(3770))} = 0.077 \ nb. \tag{6}$$

This result is obtained by using the partial width $\Gamma_{ee}(Y(4260))$ and Γ_{total} from PDG [20], and $BR(\psi(3770) \to \bar{p}p)$ from Ref. [35]. As a word of caution, the scaling in Equation (4) is only an approximation as well, as e^+ and e^- are point-like particles, but p and $\bar{p}$ are not. When scaling the partial width $\Gamma(R \to \bar{p}p)$ (or the branching fraction $BR(R \to \bar{p}p)$) for a decay to $\bar{p}p$ of a resonance $R=R_1$ with a mass m_1 to another resonance $R=R_2$ with a mass m_2, one would have to take into account, that the proton formfactor G has an energy dependence $G(\sqrt{s})$ and is changing from $\sqrt{s}=m_1$ to $\sqrt{s}=m_2$. However, we do not have to apply this correction here for the evaluation of the lower cross section limit for the $Y(4260)$, as the formfactor is already implicitely included in the measured $BR(\psi(3770) \to \bar{p}p)$).

The cross section $\sigma(\bar{p}p \to Y(4260))$ could be compared to the cross section $\sigma(e^+e^- \to Y(4260))=(62.9 \pm 1.9)$ pb [13]. For the case of the above upper limit, the cross section in the $\bar{p}p$ process is a factor of about 35 larger than the cross section measured in e^+e^- collisions.

Estimation of the produced $Z_c(3900)$ at $\overline{\text{P}}$ANDA.

The number of expected $Z_c(3900)$ events in $\overline{\text{P}}$ANDA can be estimated from Refs. [17], [23], and [34]: in the decay $e^+e^- \to J/\psi\pi^+\pi^-$ the BESIII experiment observed the $Z_c(3900)$ [17], using the full dataset collected near the $Y(4260)$ energy. The observed $Z_c(3900)$ yield is 307, and the ratio

$$R = \frac{\sigma(e^+e^- \to Z_c(3900)^+\pi^- \to J/\psi\pi^+\pi^-)}{\sigma(e^+e^- \to J/\psi\pi^+\pi^-)} = 21.5\% \ . \tag{7}$$

All measurements are based on 1.9 fb^{-1}, which is presently the world largest dataset collected at the $Y(4260)$ energy. We can extrapolate how many produced $Z_c(3900)$ are expected at $\overline{\text{P}}$ANDA, assuming that [66−1900] $Y(4260)$ states are expected to be produced per day in high resolution mode. The calculation is based upon the cross section range [77−2200] pb, as stated in the previous Section.

For the upper limit evaluation we find:

$$\sigma(\bar{p}p \to Z_c(3900)) = \sigma(\bar{p}p \to Y(4260)) \cdot 21.5\% = 0.473 \ nb \ . \tag{8}$$

For the lower limit evaluation we find:

$$\sigma(\bar{p}p \to Z_c(3900)) = \sigma(\bar{p}p \to Y(4260)) \cdot 21.5\% = 0.017 \ nb \ . \tag{9}$$

Based on these estimates, we would be able to produce [14−405] $Z_c(3900)$ events/day in high resolution mode, when running at a center-of-mass energy for $Y(4260)$ peak resonance production. We note that of course there can be non-resonant production $\bar{p}p \to J/\psi\pi^+\pi^-$ at the same energy, and the according non-resonant cross section can be even larger than the resonant cross section, although the indication from BESIII and the ISR measurements at the B factories is that non-resonant $e^+e^- \to J/\psi\pi^+\pi^-$ is small (O<10%).

$Z \leftrightarrow X$ transitions at $\overline{\text{PANDA}}$.

Observations of transitions of X, Y and Z states are very important for understanding the spectroscopical pattern, and possibly conclude similarities in the nature of these states. Two recent BESIII publications connect the $X(3872)$ to the $Y(4260)$ [18], and the $Y(4260)$ to the $Z_c(3900)$ [17]. However, up to now, no experimental measurement connects the $X(3872)$ to the Z structures. Thus, we propose to search for the transitions X to Z (or Z to X). $\overline{\text{PANDA}}$ would be well suited for this search because of the following reasons:

- about possible Z to X transitions, the decay $Z(3900) \to X(3872)\pi$ is kinematically forbidden. The decay $Z(4020) \to X(3872)\pi^0$ is allowed, however suppressed as a P-wave decay close to threshold. It may be observed at BESIII in near future. The $X(3872)$ has $J^{PC}=1^{++}$, while both the $Z(3900)$ and the $Z(4020)$ have positive parity (if L=0 is assumed). Transitions with two pions are allowed by parity, however kinematically forbidden;

- $Z(4020)^+ \to J/\psi\pi^0\pi^+$ is allowed, but no signal for the $Z(4020)$ was observed in the investigation of the according final state in searches for the charged partner of the $X(3872)$ at BaBar [36] and Belle [37];

- $\overline{\text{PANDA}}$ will collect a data set of $X(3872)$ (see above), with a statistics larger than other experiments by one or two orders of magnitude. Thus, rare decays of the X(3872), e.g. isospin forbidden decays or radiative decays, become accessible;

- as the $Z(3900)$ was observed in close vicinity of the DD^* threshold, and the $Z(4020)$ was observed in close vicinity of the D^*D^+ threshold, it is intriguing to assume the existance of another yet unboserved $Z(3730)$ in close vicinity of the $\bar{D}D$ threshold. Assuming S-wave, this state would have $J^P=0^+$, and thus it cannnot decay to $J/\psi\pi$ due to parity conservation. In fact, neither charged or neutral structure have been observed around this mass in this final state. Using the future $X(3872)$ data sample at $\overline{\text{PANDA}}$, $X(3872) \to Z(3730)\pi$ represents a candidate decay channel. The latter decay is suppressed due to isospin violation; however, isospin violating decays of the $X(3872)$, such as $X(3872)\to J/\psi\rho$, have been observed with significant branching fractions. In addition, the requirement of a J/ψ in the final state provides a tool to reduce the hadronic background at $\overline{\text{PANDA}}$. Simulations performed at the $X(3872)$ energy scan have already shown that the ratio signal over background is 6:1 [24]; therefore, a favorable ratio S/B is expected also for the search of the $Z(3730)$ resonant structures;

- due to the observation of the $Z(3900)^0$ and the $Z(4020)^0$, Z_c states have been interpreted as isospin triplets with charged and neutral partners at the same mass. Thus, we may search for the $Z(3730)^0$, which could be reconstructed from $J/\psi\gamma\gamma$ and $\chi_{c1}\pi^0$ decays. In fact, in these transitions the parity flips from $J^P = 1^+$ (the $X(3872)$) to $J^P = 0^+ \times 0^-$. Although radiative decays are suppressed by α/π, the observation of this decay would be of very high importance, as it would provide a way to measure the C-parity of the $Z(3730)^0$;

- in an additional stage, we could also search for the charged $Z(3730)^+$ candidate, decaying to $\chi_{c1}\pi^+$, with subsequent $\chi_{c1} \to J/\psi\gamma$ and $J/\psi \to$ leptons (with L=1). Investigation of other final states, e.g. $Z(3730) \to D\bar{D}$ in e.g. $p\bar{p}\to D\bar{D}\pi$ are also possible, but would suffer of higher background. Again, it should be noted that a dedicated data taking run at the center of mass energy of $Z(3730)$ is not required for the proposed study.

To summarize, $\overline{\text{PANDA}}$ would be unique to search for $X \to Z\pi$ transitions involving yet unobserved neutral and charged $Z(3730)$ states in the processes:

TABLE 1. Summary of the expected X, Y, and Z production rates per day in $\overline{\text{P}}$ANDA, assuming different operation modes (e.g. different rates $\mathcal{L}$/day). The calculation is performed by multiplying luminosity and cross sections. The cross section upper limits are used in these calculations, and in parenthesis the corresponding lower limit is reported. For the $X(3872)$, only an upper limit was evaluated in this short report, and thus we omit a second number.

Resonance	$\mathcal{L} = 8.64\ pb^{-1}/day$	$\mathcal{L} = 0.864\ pb^{-1}/day$	$\mathcal{L} = 0.432\ pb^{-1}/day$
$X(3872)$	432000	43200	21600
$Y(4260)$	19000 (665)	1900 (67)	950 (7)
$Z(3900)^+$	4050 (140)	405 (14)	202 (7)

- $\bar{p}p \rightarrow Z(3730)^0\pi^0$, $Z(3730)^0 \rightarrow J/\psi\gamma$, with $J/\psi \rightarrow$ leptons and $\pi^0 \rightarrow \gamma\gamma$;

- $\bar{p}p \rightarrow Z(3730)^0\pi^0$, $Z(3730)^0 \rightarrow \chi_{c1}\pi^0$, with $\pi^0 \rightarrow \gamma\gamma$, $\chi_{c1} \rightarrow J/\psi\gamma$ and $J/\psi \rightarrow$ leptons;

- $\bar{p}p \rightarrow Z(3730)^\pm\pi^\mp$, $Z(3730)^\pm \rightarrow \chi_{c1}\pi^\mp$, with $\chi_{c1} \rightarrow J/\psi\gamma$ and $J/\psi \rightarrow$ leptons.

We also note, that the $Z_c(3900)$ and the $Z_c(4020)$ have not been observed in B decays yet. Thus, we expect high discovery potential for $\overline{\text{P}}$ANDA.

F-wave charmonium states

A unique feature for $\overline{\text{P}}$ANDA can be the search for high spin states. Based on theoretical predictions as in Ref. [38], we simulated the multiple radiative cascade $1^3F_4(J^{PC} = 4^{++}) \rightarrow 1^3D_3(J^{PC} = 3^{--}) \rightarrow \chi_{c2}(J^{PC} = 2^{++}) \rightarrow J/\psi(J^{PC} = 1^{--})$, as detailed reported in Ref. [23]. $\overline{\text{P}}$ANDA is designed to perform an excellent photon reconstruction, and our simulations have already demonstrated that physics channels reconstructed from one J/ψ and three γ have clear signature, and a background suppression factor of about 10^6 [23]. The static heavy quark anti-quark ($\bar{Q}Q$) potential of the Cornell-type [38, 39, 40] can be expressed by $V(r) = \frac{4}{3}\frac{\alpha_s}{r} + k \cdot r$, with a chromo-electric Coulomb-type term, and a linear confinement term. It predicts many of the experimentally observed charmonium and bottomonium states up to a precision of $\approx$1 MeV. Recently several new states have been observed, which fit well into the prediction of the Cornell-type potential, i.e. the h_c, the h_b and the h'_b, or η_b and η'_b. By the mass measurements of these new states, a comparison of the level spacings between charmonium (mass region 3-4 GeV/c^2) and bottomonium (mass region 9-10 GeV/c^2) became available for the first time. For example, the following spin-averaged mass differences:

$$m(h_c) - \frac{3 \cdot m(J/\psi) + m(\eta_c)}{4} = 456.8 \pm 0.2 MeV \tag{10}$$

$$m(h_b) - \frac{3 \cdot m(\Upsilon(1S) + m(\eta_b)}{4} = 453.5 \pm 1.4 MeV \tag{11}$$

are identical to a level of better than 10^{-3}, which is quite surprising and points to flavor independence of the quark anti-quark potential. In other words, the potential does not seem to depend on the different quark mass of the charm or the bottom quark, although in the Cornell potential the quark mass is explicitly one of the adjustable parameters.

However, as already found in the 1970's [41], flavor independence is not fulfilled for a Cornell-type potential. Potentials, for which identical level spacings for charmonium and bottomonium are fulfilled, are logarithmic potentials of the type $V(r) = r_1 ln(c_2 r)$.

One of the important tasks of future experiments such as $\overline{\text{P}}$ANDA is the search for additional, yet unobserved states (e.g. the h'_c or $^3F_4$ state), which could be used to obtain additional level spacings and further test the flavor indepedence, and possibly a logarithmic shape of the potential. Simulations in this sense were performed with the $\overline{\text{P}}$ANDA full reconstruction framework [42], and they are promising, as detailed in Ref. [23, 34].

Summary

In summary, Table 1 reports our estimates for X, Y, Z production rates at $\overline{\text{P}}$ANDA, assuming different luminosity average values $L = 10^{32}$ cm^{-2}s^{-1}, $L = 10^{31}$ cm^{-2}s^{-1}, and $L = 0.5 \times 10^{31}$ cm^{-2}s^{-1}, respectively. Rates must be interpreted as educated guess, due to the $\bar{p}p$ cross sections, which have not been measured, yet. The expected large statistics at $\overline{\text{P}}$ANDA will help to address many open questions about X, Y, and Z states, in order to unravel their nature. A high discovery potential exists, in particular for new states with quantum numbers unobservable in production processes at other experimental facilities.

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