SEARCH FOR EXOTICS IN $\overline{\text{P}}$ANDA*

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At GSI is in preparation a new international research facility, called FAIR. A key feature of this new facility will be the delivery of an intense, high-quality secondary beam of antiprotons at the High Energy Storage Ring (HESR) on which the $\overline{\text{P}}$ANDA experiment will be installed. In this paper, the rich spectroscopy program on exotic hadrons of $\overline{\text{P}}$ANDA, is presented.

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1. Introduction

Though strong interaction has been studied for quite a long time, recent findings, mainly at e^+e^- machines, of new and unexpected resonances show that the hadron spectrum is not yet completely understood. This is also underlined by the ongoing discussion on multi-quark states, and other exotic states with gluonic degrees of freedom.

The $\overline{\text{P}}$ANDA (antiProton ANnihilation at DArmstadt) experiment, at the future Facility for Antiproton and Ion Research (FAIR) [1], aims at exploring this field thanks to the gluon rich environment of hadronic $\bar{p}p$ annihilation, which allows to access many final state quantum numbers, and foresees high resolution capability in production experiments. The 4π acceptance of the detector either for charged and neutral particles, together with the envisaged high production rates, will enable a clean identification even of rare channels.

These physics topics are presently under investigation inside the $\overline{\text{P}}$ANDA Collaboration and the first results of the simulation activity are the subject of "The $\overline{\text{P}}$ANDA Physics Performance Report" [2]. This is a two hundred pages document in which all the aspects of the $\overline{\text{P}}$ANDA scientific program have been deeply analyzed in order to define details and potentiality. Here, the expectations for exotic production are briefly illustrated.

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2. Exotic states

2.1. Theoretical approach

The modern theory of the strong interaction is Quantum Chromodynamics (QCD). The QCD Lagrangian is, in principle, a simple and complete description of the phenomena governed by strong force, but in spite of this simplicity, it leads to equations that are hard to be analytically solved.

In order to have a better understanding of this field, it is crucial to compare theoretical predictions to experimental results. From the theory side, two different approaches are generally used: (*i*) lattice calculations (LQCD), which attempts to solve non perturbatively QCD with numerical calculations, and (*ii*) effective field theories either with quark/gluon or with hadronic degrees of freedom, which exploit the symmetries of QCD and the existence of hierarchies of scales to provide predictions from effective Lagrangians. A key point of all the previously mentioned theoretical approaches is the prediction of exotic states. These are classified in three main categories:

- **hybrids**, *i.e.* states in which there is an explicit gluon contribution. In the simplest scenario this correspond to add the quantum numbers of a gluon to a simple $q\bar{q}$ pair. This procedure creates *e.g.* for S-wave mesons eight lowest lying hybrid states (see Tab. I);

TABLE I

The coupling of spins leads to 8 hybrid states for each pair of pseudoscalar and vector mesons with equal isospin. Even in this simple case three J^{PC} combinations are not allowed for conventional $q\bar{q}$ pairs.

	Gluon	
$q\bar{q}$	1^- (TM)	1^+ (TE)
$^1S_0$, 0^{-+}	1^{++} $\tilde{\chi}_{c1}$	1^{--} $\tilde{\psi}$
$^3S_1$, 1^{--}	0^{+-} $\tilde{h}_{c0}$ ← exotic	0^{-+} $\tilde{\eta}_{c0}$
	1^{+-} $\tilde{h}_{c1}$	1^{-+} $\tilde{\eta}_{c1}$ ← exotic
	2^{+-} $\tilde{h}_{c2}$ ← exotic	2^{-+} $\tilde{\eta}_{c2}$

- **glueballs**, composite particles that consist solely of gluons, without valence quarks. Such states are possible since gluons carry color charge, and can interact with each others. LQCD makes rather detailed predictions for the gueball mass spectrum (see Fig. 1). Glueballs are experimentally hard to be identified since they mix with ordinary mesons, therefore glueballs with exotics quantum numbers (*oddballs*) would be narrower and more easy to be detected;

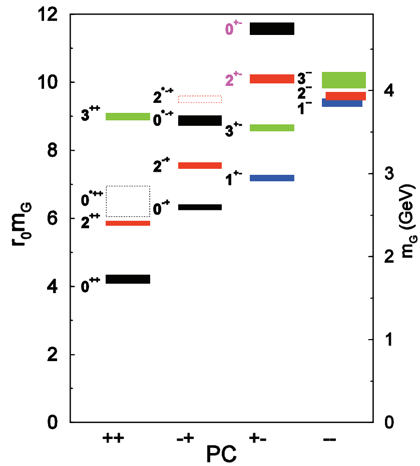

Fig. 1. Glueball predictions from LQCD calculations. See [3] for details.

- **multiquarks**, mesic excitation of $q\bar{q}$ states. These mesic excitations are expected to be loosely bound, thus resulting in large width states. Nevertheless, in the vicinity of a strong threshold this can change, and states with a potentially large additional mesic component can become narrower if they appear sub-threshold. This for example could be the case of $a_0(980)$, $f_0(975)$ system, which has a large (may be dominant) $K\bar{K}$ component in the wave function. In the case of the extremely narrow $X(3872)$ the DD^* threshold could have a similar impact on its mass explaining why is not fitting the charmonium spectrum.

2.2. The $\overline{P}ANDA$ experimental approach

Conventional and exotic mesons can be produced in a large variety of reactions, but $\bar{p}p$ annihilation has proved to be able to produce large quantities of exotic state candidates [4]. This is mostly due to the fact that the annihilation process create a lot of gluons either in formation and in production. Performing resonance scans it is possible to produce only mesons with conventional quantum number (*formation*); exotic quantum numbers can be only obtained whether an extra particle is emitted allowing spin-parity conservation (*production*).

Bump hunting in invariant mass plots will not be enough to disentangle complicated final states. Efficient triggers, and sophisticated partial wave analyses would be necessary to unambiguously identify the nature of each state. This is one of the topics of the $\overline{\text{P}}$ANDA scientific program, and in order to check the potentiality of the apparatus, that presently is under construction, an intense work of software simulations has been carried out during 2008. The results of this work are reported in "The $\overline{\mathrm{P}}$ANDA Physics Performance Report" [2], here I will briefly report some results obtained for the exotic-state search-program.

2.2.1. Hybrids

Exotic charmonia are expected to exist in the 3–5 GeV/c^2 mass region. The predictions come mainly from calculations based on bag model, flux tube model, constituent gluon model, and, recently, from LQCD [5,6]. These predictions qualitatively agree, and all models expect that the lightest exotic state would be a 1^{-+}. Predictions for the mass and the width set the values around 4.3 GeV/c^2, and 20 MeV/c^2, respectively. In addition, there are seven other hidden charmed hybrids to be discovered. Therefore, the main goal would be to measure the whole pattern of charmonium exotic states.

Charmonium hybrids are likely to be narrow, since open-charm decays are forbidden or suppressed below the $D\overline{D}^*_J$ + c.c. threshold. From experiments at LEAR we know that production rates of states with exotic quantum numbers are similar to those of $q\bar{q}$ states. Thus, we estimate that the cross sections for the formation and production of charmonium hybrids will be of the same order of magnitude of normal charmonium states (*e.g.* ~ 120 pb for $\bar{p}p \to J/\psi\pi^0$ [7]).

Our program to search for charmonium hybrids foresees, as a first step, production measurements at the highest antiproton energy available ($E_{\bar{p}} =$ 15 GeV, $\sqrt{s} = 5.46$ GeV/c^2) for studying all possible channels: exotic and conventional. The next step would consist of formation measurements to scan the antiproton energy in small steps in the regions where promising hints of hybrids have been observed in the production phase. From the eight hybrid states, it is possible to measure seven of them using three channels with a charmonium final state:

$$\begin{aligned} \bar{p}p &\to \tilde{\eta}_{c0,1,2}\eta \to \chi_{c1}\pi^0\pi^0\eta\,, && (1)\\ \bar{p}p &\to \tilde{h}_{c0,1,2}\eta \to J/\psi\pi^0\pi^0\eta\,, && (2)\\ \bar{p}p &\to \tilde{\psi}\eta \to J/\psi\omega\left[\pi^0 \text{ or } \eta\right]\,. && (3) \end{aligned}$$

Although a charmonium final state is likely, an open charm final state may also be possible and seven of the already mentioned eight states may be accessed with the final state DD^*. Thus the reactions

$$\bar{p}p \to \left[\tilde{\eta}_{c0,1,2}, \tilde{h}_{c0,1,2}, \tilde{\chi}_{c1}\right]\eta \to DD^*\eta \tag{4}$$

has also been used as a benchmark channel.

Finally, since the new experimental findings $Y(3940)$ [8], and $Y(4320)$ [9] are also discussed in the framework of hybrids, they have been simulated as hybrid benchmark channels.

2.2.2. Glueballs

LQCD predicts the presence of about fifteen glueballs in the mass range accessible to the $\overline{\text{P}}$ANDA experiment, some with exotic quantum numbers. The lightest oddball, with $J^{PC} = 2^{+-}$, has been predicted with a mass of 4.3 GeV/c^2. Like charmonium hybrids, glueballs can either be formed directly in the $\bar{p}p$-annihilation process, or produced together with another particle. In both cases, the glueball decay into final states like $\phi\phi$ or $\phi\eta$ would be the most favorable below 3.6 GeV/c^2, while $J/\psi\eta$ and $J/\psi\phi$ are the first choices for the more massive states.

The indication for a tensor state around 2.2 GeV/c^2 was found in the experiment JETSET at LEAR [10]. The acquired statistics was not sufficient for the complementary reactions to be determined. We plan to measure the $\bar{p}p \to \phi\phi$ channel with statistics of two orders of magnitude higher than in the previous experiments.

2.2.3. Simulation results

The offline software which has been used for simulating the benchmark channels reported in "The $\overline{\text{P}}$ANDA Physics Performance Report" [2] consists in a chain of packages that reproduce at best the spectrometer behavior. It consists of: the event generator, the particle tracking transport code (based on GEANT4), the digitization algorithm to model the signal of each sub-detector on the proper front-end electronics, the particle identification and reconstruction system, and finally several well-tested software tools and packages from other HEP experiments adapted to the $\overline{\text{P}}$ANDA setup to perform a complete and realistic analysis path.

In order to give here an hint of the $\overline{\text{P}}$ANDA possibilities, I report briefly the results of the simulations performed for the hybrid benchmark channels. More details on the complete set of simulations can be found in Ref. [2].

To test the spectrometer capability to detect an hypothetical hybrid $\tilde{\eta}_{c1}$ we generated $2{\times}10^5$ events of reaction (1) with $\chi_{c1} \to J/\psi\gamma$ and the $J/\psi \to e^+e^-$ at the maximum $\bar{p}$ momentum: 15 GeV/c. Therefore, this final state has seven γ and one e^+e^- pair originated from J/ψ decay. Source of background are reactions like: $\bar{p}p \to \chi_{c0}\pi^0\pi^0\eta$, $\bar{p}p \to \chi_{c1}\pi^0\eta\eta$, $\bar{p}p \to \chi_{c1}\pi^0\pi^0\pi^0\eta$ and $\bar{p}p \to J/\psi\pi^0\pi^0\pi^0\eta$. The hypothetical hybrid state is absent in these reactions, but the χ_{c0} and χ_{c1} mesons decay via the same decay path as for the signal. Therefore, these events have a similar topology as signal events and could potentially pollute the $\tilde{\eta}_{c1}$ signal. For each background reaction we generated also 2×10^5 events. The invariant $\chi_{c1}\pi^0\pi^0$ mass obtained after the application of all the selection criteria (Fig. 2 (a)) has a FWHM of 30 MeV/c^2. The reconstruction efficiency is found to be 6.83%. Depending on the background channel the S/B is varying between 250–10100 $\mathcal{R}$, with $\mathcal{R} = \frac{\sigma_{\rm S}\mathcal{B}(\tilde{\eta}_{c1}\to\chi_{c1}\pi^0\pi^0)}{\sigma_{\rm B}}$.

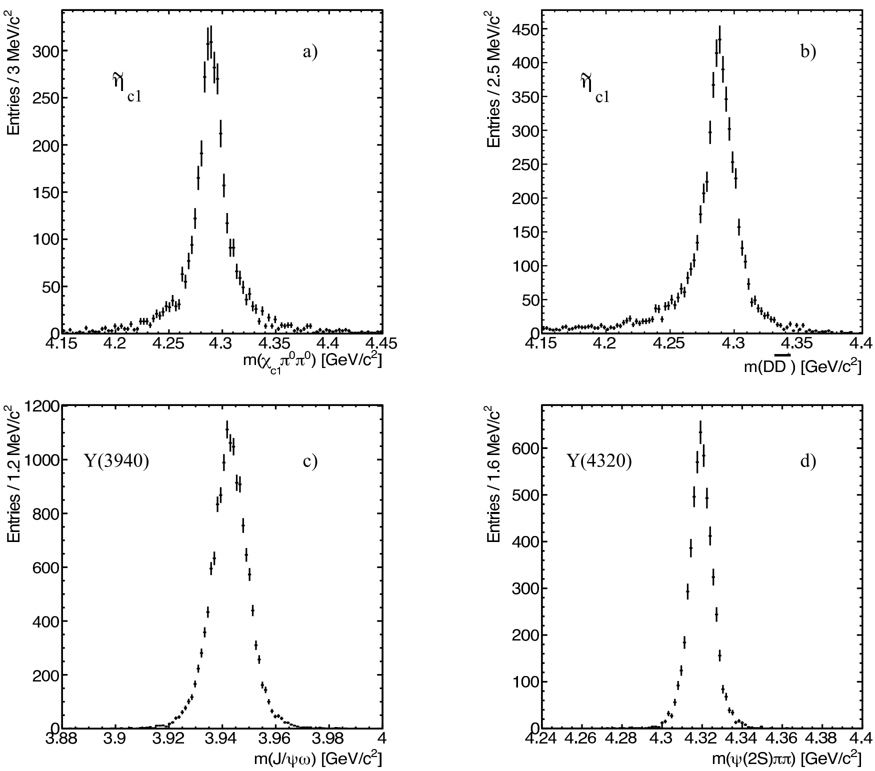

Fig. 2. Invariant mass distributions of different reactions: (a) $\bar{p}p \to \tilde{\eta}_{c1}\eta, \tilde{\eta}_{c1} \to \chi_{c1}\pi^0\pi^0$; (b) $\bar{p}p \to \tilde{\eta}_{c1}\eta, \tilde{\eta}_{c1} \to D^0\overline{D}^{*0}$; (c) $\bar{p}p \to Y(3940), Y(3940) \to J/\psi\omega$; (d) $\bar{p}p \to Y(4320), Y(4320) \to \psi(2S)\pi^+\pi^-$. More details are in the text.

For the channel $\bar{p}p \to \tilde{\eta}_{c1}\eta \to DD^*\eta$ two possible background reactions have been investigated: $\bar{p}p \to D^0\overline{D}^{*0}\pi^0$, where the recoil η is absent and the D and D^* mesons decay via the same decay path as for signal events, and the reaction $\bar{p}p \to D^0\overline{D}^{*0}\eta$, where the recoil η is present but either the D^0 or the $\overline{D^0}$ meson (from $\overline{D}^{*0} \to \overline{D}^0\pi^0$ decay) is decaying into $K^\pm\pi^\mp\pi^0\pi^0$. The obtained $D^0\overline{D}^{*0}$ invariant mass distribution, showed in Fig. 2 (b), has a FWHM of 22.5 MeV/c^2, and the reconstruction efficiency is 5.17%. The background reactions have been suppressed by a factor $>1.6\times10^5$.

$Y(3940)$ has been studied in formation in an exclusive channel: $\bar{p}p \to Y(3940) \to J/\psi\omega$, with the J/ψ identified via the e^+e^- decay mode, and the ω via the three pions final state. The final reconstruction efficiency for the signal events is 14.7%. The invariant mass distributions obtained after all the kinematic fit applying the $J/\psi, \pi^0$, and $Y(3940)$ mass constraints is shown in Fig. 2 (c). The FWHM is 14.4 MeV/c^2. A very good background suppression better than 1×10^9 and 1×10^8 is achieved for the channels $\bar{p}p \to \pi^+\pi^-\pi\rho$ and $\bar{p}p \to \pi^+\pi^-\omega$, respectively. For the other reactions considered $\bar{p}p \to \psi(2S)\pi^0$ and $\bar{p}p \to J/\psi\pi\rho$ a background suppression factor of about 3×10^3 and >20 has been determined.

For $Y(4320)$ we considered the following reaction: $\bar{p}p \to \psi(2S)\pi^+\pi^-$, $\psi(2S) \to J/\psi\pi^+\pi^-, J/\psi \to e^+e^-$ at a beam momentum of 8.9578 Gev/c corresponding to the mass of the resonance examined. Here the main source of background is the reaction $\bar{p}p \to 3\pi^+3\pi^-$ that nevertheless can be rejected at the level of 10^7. The final efficiency for the signal reconstruction is 14.9% with a FWHM of the invariant mass plot of 13 MeV/c^2 (see Fig. 2 (d)).

3. Conclusions

With extended simulations, the $\overline{\text{P}}$ANDA Collaboration has shown that $\bar{p}p$ annihilation is a fruitful environment to study exotic states. Signals are expected to have reasonable cross-sections, and the most important background processes could be eliminated with good rejection factors. What is mandatory, to make these predictions real, it is to have an excellent detector combined with a high-luminosity and high-resolution antiproton beam.

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