Physics with Antiprotons at PANDA

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Abstract. The PANDA experiment is part of the core project of the planned Facility for Antiproton and Ion Research (FAIR) at GSI in Darmstadt (Germany)[1]. One major component of the upgraded accelerator complex is the High Energy Storage Ring (HESR) which will provide a high quality antiproton beam in the momentum range between 1.5 and 15 GeV/c. PANDA, a fixed target experiment directly implemented in the HESR, will investigate antiproton annihilations with the aim to explore fundamental questions in the crossover region of the non-perturbative and strong QCD. Due to the planned extensive physics program a multipurpose detector with a nearly complete solid angle coverage, proper particle identification over a large momentum range, and high resolution calorimetry for neutral particles is required.

After an overview about the goals and the detector design of the PANDA experiment major parts of the planned physics program will be discussed, namely the meson spectroscopy and the search for exotics in the charmonium and open charm region.

1. Introduction
In the framework of QCD the interaction between quarks is described by exchanging virtual gluons. At short distances experimental data can be explained via perturbation theory with high precision. The perturbation theory fails in the regime of distances in the order of the size of the nucleon, and theoretical approaches are required. The self-interaction of gluons makes the forces stronger with increasing distances of the interactive particles. Accurate and high statistic measurements of the complete meson spectrum in the charmonium region below and above the $D\bar{D}$ breakup threshold are one fundamental key to improve the knowledge of this crossover region of the non-perturbative and perturbative QCD. Another consequence of the gluon self-interaction is the prediction of hadronic systems like glueballs which consist only of gluons and hybrids which are bound systems of quark-antiquark pairs with one or more gluons. The PANDA experiment will investigate especially this partly not well known region of the QCD by studying the gluon rich process of antiproton annihilation with hydrogen and nuclear targets. Hadrons in the energy range up to $\sqrt{s} = 5.5$ GeV/c can be produced so that predicted unobserved charmonia as well as the spectrum of charmed hybrids and glueballs are accessible.

2. The PANDA experiment
The existing GSI accelerator complex will be upgraded and thus undergo drastic changes in the next years. The ion beam will be increased in intensity and energy with the aim to provide antiprotons for several experiments. PANDA is planned as a fixed target experiment and will be integrated in the High Energy Storage Ring (HESR) which provides an antiproton beam in the momentum range between 1.5 GeV/c and 15 GeV/c. To ensure an excellent beam quality...
the ring will be equipped with stochastic cooling over the whole momentum range so that a luminosity of $L = 10^{32} cm^{-2}s^{-1}$ and a momentum spread of $\delta p/p = 10^{-4}$ will be achieved. For high-precision charmonium spectroscopy electron cooling for momenta up to 8 GeV/c is foreseen in addition. This so called high resolution mode will provide a momentum spread of about $\delta p/p = 10^{-5}$. With these conditions PANDA will study the following physics cases (Fig. 1):

- Spectroscopy of charmonium states and investigation of open charm production,
- search for exotic matter like glueballs and hybrids including the QCD predicted excitations in the charmonium range,
- light meson spectroscopy which allows comparisons with previous LEAR results,
- extraction of generalized parton distributions from $\bar{p}p$ annihilations,
- baryon and anti-baryon production with the possibility to study CP violation,
- behavior of charmonium states in nuclear medium and
- precise $\gamma$-ray spectroscopy of single and double hypernuclei.

For this extensive physics program a multipurpose detector is required which has to fulfill the following characteristics:

- Due to the planned exclusive measurements the detector has to cover nearly the full solid angle with good spatial and momentum resolution for charged as well as for neutral particles,
- particle identification (PID) in a large momentum range up to approximately 10 GeV/c for $\gamma, e, \mu, \pi, K$ and $p$,
- proper vertex resolution in the order of 100 $\mu m$,
- operation at high event rates of approximately $10^7/s$,
- and a sophisticated trigger for the accumulation of rare decay modes.

The planned PANDA detector is illustrated in Fig. 2. The detector is subdivided into two main parts: The target spectrometer with a solenoid field and the forward spectrometer with a large acceptance dipole magnet.

The target spectrometer surrounds the interaction region and is embedded in a 2 T solenoid field. The Micro Vertex Detector (MVD) and the Straw Tube Tracker (STT) or the alternative solution of a Time Projection Chamber (TPC) combined with Mini Drift Chambers (MDC) for the tracking, and the EMC for the detection of neutral particles are covering polar angles of $10^\circ - 170^\circ$ in the laboratory frame. The region below $10^\circ$ is covered by the forward spectrometer.
which includes a 1 meter gap dipole and tracking detectors like MDC or STT. Photons will be detected by a shashlyk type calorimeter consisting of lead-scintillator sandwiches. In addition devices for particle identification are foreseen for both parts of the spectrometer. Particles with momenta above approximately 1 GeV/c will be identified with Cherenkov detectors while the identification of the low momenta particles will be done via energy loss and/or time of flight measurements. Counters for the detection of muons are located within the yokes of the magnets.

Figure 2. Top view of the PANDA detector.

For the comparison and optimization of the different favoured detector scenarios investigations of specific benchmark channels have already been started. These first systematic studies cover the most relevant physics topics (Tab.1) and partly allow a comparison with well known results from other experiments. The major objectives of these studies are serious estimates for reconstruction efficiencies, background rejection power as well as resolution functions for the whole detector. A summary of all preliminary results is given in [2]. More detailed studies with a larger number of benchmark channels are foreseen in the near future.

3. The physics program of PANDA

The following section will give an overview of the central part of the physics program of PANDA: The meson spectroscopy and the search for exotic matter in the charmonium range. The gluon rich antiproton proton reactions with the advanced beam cooling techniques are an excellent source to address the still open questions of the charmonium spectrum below and above the open charm threshold and to search for exotic states like charmed hybrids and glueballs.

3.1. Charmonium spectroscopy

The presently known charmonium states and the determination of their properties are mainly originated from measurements of $e^+e^-$ reactions. Although a couple of new states have been
Table 1. Benchmark channels for the optimization of the PANDA detector.

| Benchmark channel          | $\bar{p}$ momentum [GeV/c] | Physics case                      |
|----------------------------|-----------------------------|-----------------------------------|
| $\bar{p}p \rightarrow \psi(3770) \rightarrow DD$ | 6.57                        | Open Charm Production             |
| $\bar{p}p \rightarrow \psi(4040) \rightarrow D^* D*$ | 7.70                        | Open Charm Production             |
| $\bar{p}p \rightarrow \eta_c \rightarrow \gamma \gamma$ | 3.68                        | Electromagnetic Charmonium Decay  |
| $\bar{p}p \rightarrow \eta_c \rightarrow K^0_S K^0 \pi^+$ | 3.68, 15.15                 | Meson Spectroscopy                |
| $\bar{p}p \rightarrow \psi_0 \eta \rightarrow \chi_c \pi^0 \pi^0 \eta$ | 15.15                       | Exotic Charmed Hybrid             |
| $\bar{p}p \rightarrow \gamma \gamma$ | 3.68, 5.89, 9.8, 15.15      | Crossed Channel Compton Scattering |
| $\bar{p}p \rightarrow \eta_c \rightarrow \phi \phi \rightarrow 2K^+ 2K^-$ | 3.68                        | Charmonium $\phi$-Decay          |
| $\bar{p}p \rightarrow \Lambda \Lambda \rightarrow \rho \pi^- \bar{p} \pi^+$ | 2.0, 4.0, 6.0, 7.7       | Strange Baryon Production         |
| $\bar{p}A \rightarrow J/\psi X \rightarrow \mu^+ \mu^- X$ | 4.05                        | Charmonium Absorption in Nuclei   |

observed during the last years which results in some highlights in this domain of particle physics, the overall knowledge is still poor. Experiments based on different production mechanisms are very helpful to improve the present knowledge of the charmonium spectrum. Especially the antiproton proton reactions provide a versatile tool in this context. Unlike in $e^+e^-$ reactions, where only states with the quantum numbers of the intermediate virtual photon ($J^{PC} = 1^{--}$) can be formed directly, the $\bar{p}p$ annihilation allows the formation of charmonia with any combinations of initial quantum numbers. As a consequence mass scans can be performed by changing the beam momentum in small steps. This allows high accurate measurements since the resolution for the scanned resonances is limited only by the momentum spread of the beam and not by the performance of the detector. This has already been demonstrated by the excellent results achieved with the experiments E760 and E835 at the Fermilab antiproton accumulator. The charmonium spectroscopy program of PANDA will be an extension of these successful experiments performed recently at Fermilab. The advantages of the planned PANDA experiment are the possibility to take data with a higher luminosity for the $\bar{p}p$ reactions or alternatively to measure with a better beam spread of approximately one order of magnitude improvement instead. Furthermore a higher maximum beam momentum can be achieved so that open charm resonances up to $\sqrt{s} = 5.5 \text{GeV}/c^2$ are accessible, and a state of the art detector with higher rate capacity will be available.

3.1.1. Charmonium states below the open charm threshold. At a first view the situation of the charmonium spectrum below the open charm threshold seems to be well understood. All eight states predicted by several potential models have already been observed (Fig. 3). The best understanding has been achieved for the $\psi$ resonances which can be produced directly in the $e^+e^-$ formation mode. The last missing charmonium state in this mass region was the $h_c$ which could be recently identified by the E835 collaboration in the process $\bar{p}p \rightarrow h_c \rightarrow J/\psi \pi^0$ [3] and by the CLEO experiment via the decay mode $h_c \rightarrow \eta_c \gamma$ [4]. Due to the fact that the strong decay modes are completely suppressed for charmonia below the open charm threshold, the widths of all these states are very narrow. While precise measurements for the $1^{--}$ states could already be done in $e^+e^-$ experiments, the accuracy of the properties for the non $1^{--}$ states is still poor.

The charmonium spectrum can be described by nonrelativistic quark models which typically contain three ingredients: the nonrelativistic quark kinetic energy, a central confining potential, and a variety of spin dependent corrections [5]. Accurate and high statistic measurements of the non $1^{--}$ states are an important diagnostic for the third contribution, the spin dependent
corrections. The following open questions have to be answered in this context:

- Properties of the $\eta_c$ and its first excitation: the $\eta_c(2S)$
  High precision measurements of the mass and width of the $\eta_c$ are extremely important for the accurate determination of the groundstate vector-pseudoscalar splitting $M(J/\psi) - M(\eta_c)$. The $\eta_c(2S)$, also known as $\eta_c^*$, was recently discovered by Belle in hadronic $B$-decays [6] and was confirmed by CLEO [7] and BaBar [8, 9, 10] in $\gamma\gamma$ collisions, in the $e^+e^-$ formation mode, and also in $B$-decays. Due to the limited statistics and systematical limitations of $e^+e^-$ machines a $\bar{p}p$ scan could be helpful to compare the experimental results with the theoretical expectations for the excited vector-pseudoscalar splitting with the $\psi'$.

- Mass, width, decay modes and branching ratios of the $h_c$
  The comparison of the singlet P state $h_c$ with the corresponding triplet states $\chi_{cJ}$ is the most important key for the determination of the spin-dependent components of the $c\bar{c}$ confining potential. Only few measurements of the properties of the $h_c$ could be done so far. The PANDA experiment is able to measure this state via the formation mode in $\bar{p}p$ reactions with high accuracy and statistics and therefore to carry out a systematic study of its mass, width, decay modes and branching ratios.

3.1.2. **Charmonium states above the open charm threshold.** The investigation of the states above the $D\bar{D}$ threshold is the central part of the charmonium program of PANDA. The spectrum of this region is partly very poorly known. Four $1^{−−}$ states have already been observed by $e^+e^−$ experiments (Fig. 3). While the $\psi(3770)$ is well established, lots of more investigations are needed for the three other states, the $\psi(4040)$, the $\psi(4160)$ and the $\psi(4415)$. Among other things almost nothing is known about the exclusive decay modes of these three resonances. Another interesting issue is the coupling of the orbitary excited vector mesons to $p\bar{p}$ reactions with high accuracy and statistics and therefore to carry out a systematic study of its mass, width, decay modes and branching ratios.

The knowledge of the non $1^{−−}$ states are even less. The recent discoveries of a couple of new resonances, the so called $X$, $Y$ and $Z$ resonances, are one of the most interesting topics in the charmonium spectroscopy nowadays. Since the nature of these states is still unclear a lot of different scenarios for their interpretation are under discussion. One prominent example is the $X(3872)$ which was discovered in 2003 by Belle in $B$-meson decays [12] and which afterwards was confirmed by several other experiments. Due to the unusual properties like the small width or the mass which is very close to the $D\bar{D}^*$ threshold, the speculations ranges from a normal excited charmonium state to the interpretation of a $D^0\bar{D}^{*0}$ molecule.

PANDA is an excellent experiment to address all these open questions mentioned above and can contribute in addition to find many still unobserved charmonia which are expected in this mass region. The required exclusive measurements with high statistics or alternatively with high accurate mass-scans in the formation mode can be fulfilled in an excellent way.

3.2. **Exotics: Hybrids and glueballs**

The QCD, the established theory for the description of the strong interaction, is a non-Abelian gauge theory. One essential consequence of this theory is the self-interaction of the gauge bosons, the gluons. Therefore hadronic systems apart from the naive quark model can exist, the so called exotics. One kind of such exotic hadronic systems are glueballs which are predominantly bound states of excited gluons. Hybrids are another type of such exotics which consist of a $q\bar{q}$ pair with one or more excited gluons in addition. The additional degrees of freedom carried by the gluons allow quantum numbers like $J^{PC} = 0^{−−}, 0^{++}, 1^{−−}$, or $2^{++}$ which are forbidden for normal $q\bar{q}$ mesons and other fermion-antifermion systems. These exotic quantum numbers provide the
best signature to distinguish gluonic hadrons from $q\bar{q}$ states. The most promising results for the search of hybrids and glueballs came from experiments which studied the gluon rich antiproton annihilation process in the mass region of the light-quark mesons up to 2.2 GeV/$c^2$. One of the most prominent particle with quantum numbers $J^{PC}=1^{-+}$, the $\pi_1(1400)$ [14], has been unambiguously seen in $p\bar{p}$ annihilation at rest. Because its combination of quantum numbers is exotic this state cannot be an ordinary meson. Furthermore the $f_0(1500)$ with non-exotic quantum numbers $J^{PC}=0^{++}$ was also discovered in $p\bar{p}$ annihilation and is considered as the best candidate for the glueball ground state. However it seems to mix with nearby ordinary $0^{++}$ states, which makes the unique interpretation as a glueball more difficult. Such mixtures are a general challenge for the doubtless interpretation of the nature of states in the light-quark meson region. The abundance of mostly broad resonances is so large that there is always mixing between states with the same quantum numbers.

Until now the search for exotics was mainly focused on the mass region below 2.2 GeV/$c^2$. The following two different aspects are good arguments to go also to higher masses up to 5.5 GeV/$c^2$:

- The high density and the broad width of normal $q\bar{q}$ light-quark states make it difficult to identify exotics with masses below approximately 2.2 GeV/$c^2$ in a proper way. In particular only eight narrow states exist in the charmonium region below the $D\bar{D}$ threshold where potential exotics can be simply identified.

- All calculations based on established theories predict that the lowest lying charmed hybrids ($c\bar{c}g$) and the first excited glueball states should exist in the mass range from approximately 2.2 GeV/$c^2$ up to 5.5 GeV/$c^2$. Due to the lower density of normal $q\bar{q}$ states it should be possible to identify unambiguously these potential exotics.

Therefore the PANDA experiment will mainly focus the search for exotics in the charmonium mass range up to $\sqrt{s} = 5.5\text{GeV}/c^2$. By studying the formation mode of the $p\bar{p}$ annihilation process only gluonic hadronic systems with non-exotic quantum numbers are accessible. States with exotic quantum numbers can be generated in production mode with usually one $\pi$ or $\eta$ as recoil particle.

3.2.1. Charmed hybrids. The predictions for hybrids are based on several different models and, recently with increased precision, on Lattice Quantum Chromodynamics (LQCD).
theoretical results agree qualitatively and even the predicted properties seem to be not so far from reality. A couple of the first lowest lying charmed hybrids are predicted in the mass range between 4.0 and 5.5 \( GeV/c^2 \). Three of them have spin-exotic quantum numbers \( J^{PC} = 0^{-+}, 1^{--}, \) and \( 2^{+-} \). Since mixing with nearby \( c\bar{c} \) states is excluded, these three potential hybrids could be easily discovered. Compared to the light hybrid candidates also the charmed hybrids with non-exotic quantum numbers should be easier to identify, since the widths of these states are expected to be narrower. The reason is that open charm decays are forbidden or suppressed below the \( D\bar{D}^*_J + c.c. \) threshold. Based on the LEAR measurements the production rates of light \( q\bar{q} \) resonances are similar to the exotic states observed in this mass region. Generalizing this to the charmed hybrid case, cross sections in the order of 100 \( pb \) are expected [15].

3.2.2. Glueballs. LQCD predictions for the glueball spectrum are rather detailed [16, 17]. About 15 glueballs with masses below 5.0 \( GeV/c^2 \) are expected (Fig. 4). The ground state with the quantum numbers \( J^{PC} = 0^{++} \) is calculated with a mass of approximately 1.7 \( GeV/c^2 \) and a width of about 100 \( MeV/c^2 \). The measured properties of the \( f_0(1500) \), which likely contains the dominant admixture of the \( 0^{++} \) glueball are in good agreement with these calculations. The remaining 14 candidates are expected in the mass range between 2.4 and 4.8 \( GeV/c^2 \) so that all of them are accessible with the PANDA experiment.

![Figure 4. Glueball mass spectrum predicted from LQCD calculations. [16, 17].](image)

The lowest lying glueball with exotic quantum numbers is predicted with a mass of 4.3 \( GeV/c^2 \). Due to the fact that this \( 2^{+-} \) state cannot mix with normal mesons, the width of this particle is expected to be rather narrow and thus easy to identify [18]. Since glueballs should decay flavor blind, \( \phi\phi \) and \( \phi\eta \) are the most promising channels for the discovery of this kind of exotics in the mass region below 3.6 \( GeV/c^2 \). The decay channels \( J/\psi \phi \) and \( J/\psi \eta \) are the first choice for the identification of more massive glueballs.

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