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Physics with the $\overline{\text{P}}$ANDA detector at GSI

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Abstract. The $\overline{\text{P}}$ANDA experiment, which will be installed at the High-Energy Storage Ring (HESR) of the recently approved FAIR facility at GSI in Darmstadt, Germany, has a rich experimental program of hadron spectroscopy which includes the study of charmonium, the search for glueballs and hybrids and the investigation of in-medium modifications of hadrons as they interact with nuclear matter.

1. Introduction

The GSI laboratory in Germany has recently approved a major upgrade of its accelerator complex [1]. The upgraded facility, called FAIR (Facility for Antiproton and Ion Research) will become fully operational by 2012. The central part of FAIR is a synchrotron complex consisting of two separate synchrotron accelerator rings with the same circumference and housed in the same tunnel. One of the goals of this synchrotron complex will be to provide intense pulsed (2.5×10^{13}) proton beams at 29 GeV. An antiproton beam will then be produced by the primary proton beam. Antiprotons will be produced with a rate of approximately $2 \times 10^7/s$ and then stochastically cooled; after 5×10^{10} $\overline{p}$ have been stored they will be transferred to the High-Energy Storage Ring (HESR) where internal experiments can be performed and where the $\overline{\text{P}}$ANDA ($\overline{p}$ ANnihilations at DArmstadt) detector will be installed.

The antiproton beam momentum will vary between 1 and 15 GeV/c; thus the maximum center-of-mass energy will be approximately 5.5 GeV, sufficient for associated production of singly charmed baryons up to the Ω_c and corresponding to the upper mass range predicted for charmonium hybrid states.

Stochastic cooling of the beam over the whole energy range to a momentum spread $\delta p/p \approx 10^{-4}$ is an essential requirement. In order to perform high-precision charmonium spectroscopy, beam properties below 8 GeV/c ($\overline{p}$ momentum) will be improved by high-energy electron cooling, which will allow to reach $\delta p/p \approx 10^{-5}$, albeit at a reduced luminosity. The antiproton beam will hit the internal hydrogen target of the $\overline{\text{P}}$ANDA experiment. With this arrangement the maximum luminosity will be $2 \times 10^{32} cm^{-2} s^{-1}$.

The $\overline{\text{P}}$ANDA collaboration has proposed a rich experimental program to study fundamental questions of hadron and nuclear physics and to carry out precision tests of the strong interaction. This program includes the study of charmonium spectroscopy, the search for glueballs and hybrids in the charmonium mass region and the investigation of in-medium modifications of hadrons as they interact with nuclear matter. These topics will be briefly reviewed in the following sections. Other items in the $\overline{\text{P}}$ANDA physics program, not discussed in this review, include the spectroscopy of single and double hypernuclei and the study of electromagnetic processes.

2. Charmonium Spectroscopy

The charmonium spectroscopy physics program of $\overline{\text{P}}$ANDA is an extension of successful experiments performed recently at the Fermilab antiproton accumulator (E760 and E835). Advanced $\overline{p}$ cooling techniques and a more versatile detector setup will be employed, allowing for the first time the measurement of both electromagnetic and hadronic decays. The goal is to make comprehensive measurements of the spectroscopy of the charmonium system and hence provide a detailed experimental study of the QCD confining forces in the charm region to complement theoretical investigation. Some of the currently "hot" topics in charmonium spectroscopy are briefly reviewed in the following subsections.

Unlike e^+e^-, where only states with the quantum numbers of the photon ($J^{PC} = 1^{--}$) can be formed directly, all quantum numbers are directly accessible in $\overline{p}p$ annihilation. Charmonium states are studied by accelerating the $\overline{p}$ beam to the energy of the resonance, which is then scanned by changing the beam momentum in small steps.

2.1. Charmonium below Open Charm Threshold

All eight states below threshold have been observed, but our knowledge of the system is far from complete.

Despite the abundance of measurements (more than 5 in the past two years) the agreement between the various determinations of the η_c mass and width is not satisfactory [2]: the Particle Data Group (PDG) average for the mass has a confidence level of only 0.001, whereas individual measurements of the width range between 7 and 34 MeV. New, high-precision measurements of these paramters are extremely important (particularly the total width) and, furthermore, the unexpectedly large value of the total width needs to be understood.

The study of the $\eta_c(2S)$ meson has just started. It was discovered by the Belle experiment in hadronic B decays [3] and was confirmed by CLEO [4] and BaBar [5] in $\gamma\gamma$ collisions. Its properties are incompatible with earlier findings by the Crystal Ball [6] and are only marginally consistent with most model calculations. The accuracy for the total width is only 50 %. Due to limited statistics and the systematical limitations of e^+e^- machines (including the B factories) it is a $\overline{p}p$ scan which will finally settle these questions.

The singlet P state of charmonium h_c is of extreme importance in determining the spin-dependent components of the $c\overline{c}$ confining potential. The h_c was first observed and positively identified by E760 in the process $\overline{p}p \to h_c \to J/\psi\pi^0$ [7] with a mass of (3526.2 ± 0.3) MeV/c^2. Due to the limited statistics only an upper limit for the width at 1.1 MeV could be set. The h_c has subsequently been observed by the E835 collaboration in the process $\overline{p}p \to h_c \to \eta_c\gamma \to \gamma\gamma\gamma$ [8] and by the CLEO collaboration in the decay mode $h_c \to \eta_c\gamma$ with the η_c decaying to hadrons [9]. The mass values of E835 and CLEO agree with each other and with the E760 result. It must be pointed out that due to the very narrow width and expected low yields only a $\overline{p}p$ experiment like $\overline{\text{P}}$ANDA will be able to measure the h_c width and to carry out a systematic study of its decay modes.

The angular distributions in the radiative decays of the χ_{cJ} states must be studied with high statistics, to shed light on the small discrepancy between the present measurements [10, 11] and the theoretical predictions. These decays are dominated by the dipole term E1. Higher multipoles arise in the relativistic treatment of the interaction between the electromagnetic field and the charmonium system.

2.2. Charmonium above Open Charm Threshold

Above the $D\overline{D}$ threshold at 3.73 GeV very little is known with any certainty. Yet this is the region in which narrow ${}^1D_2$, ${}^3D_2$ states (which are narrow because they cannot decay to $D\overline{D}$) and the first radial excitations of the singlet and triplet P states are expected to exist. It is important to identify and study the P- and D-states. Observation of the ^3D_J states would be important in testing the Lorentz nature of the confining potential.

An important discovery in this energy region has been made by the Belle experiment, which in 2003 reported the observation of a new narrow state in the decays of the B meson with a mass of 3872.0 MeV/c^2 [12]. This new state, called X(3872), has subsequently been observed by CDF [13], D0 [14] and BaBar [15]. The nature of this new, narrow state is not yet clear, and speculation ranges from a $D^0\overline{D^{0*}}$ molecule to a $^3D_2$ state. There are theoretical problems with all these interpretations, and further, more accurate measurements of its width and particularly of its decay modes are needed to shed light on this question. This kind of study is ideally suited for a $\overline{p}p$ formation experiment.

The study of the energy region above the $D\overline{D}$ threshold is a central part of the charmonium physics program of $\overline{\text{P}}$ANDA. It will require high-statistics, small-step scans of the entire energy region accessible at GSI.

3. Hybrids and Glueballs

The QCD spectrum is much richer than that of the naive quark model, as the gluons, which mediate the strong force between quarks, can also act as principal components of entirely new types of hadrons. These "gluonic hadrons" fall into two general categories: glueballs and hybrids. Glueballs are excited states of pure glue, while hybrids are resonances consisting largely of a quark, an antiquark and excited glue. The additional degrees of freedom carried by gluons allow glueballs and hybrids to have spin-exotic quantum numbers J^{PC}, which are forbidden for normal mesons and other fermion-antifermion systems. Exotic quantum numbers (e.g. $J^{PC} = 0^{--}, 0^{+-}, 1^{-+}, 2^{+-}$) are the easiest way to distinguish gluonic hadrons from $q\overline{q}$ states, but even non-exotic glueballs and hybrids can be identified by measuring an overpopulation of the experimental meson spectrum and by comparing their properties (masses, quantum numbers, decay channels etc.) with predictions from models or Lattice QCD (LQCD). Since the properties of glueballs and hybrids are determined by the long-distance features of QCD, their study will yield fundamental insights into the structure of the QCD vacuum.

The most promising result for gluonic hadrons in recent years comes from antiproton annihilation experiments. Two particles with spin-exotic $J^{PC} = 1^{-+}$ quantum numbers, $\pi_1(1400)$ [16] and $\pi_1(2200)$ [17], are clearly seen in $p\overline{p}$ annihilation at rest. In the search for glueballs a narrow state at 1500 MeV/c^2, discovered in antiproton annihilations, is considered the best candidate for the glueball gound state ($J^{PC} = 0^{++}$). However it mixes with nearby conventional 0^{++} $q\overline{q}$ states, which makes the unique interpretation as glueball more difficult.

3.1. Charmed Hybrids

Until now the search for glueballs and hybrids was mainly restricted to the mass region below 2.2 GeV/c^2. Because of the unavoidable problems due to the high density of normal $q\overline{q}$ mesons below 2.5 GeV/c^2 it would be experimentally very rewarding to go to higher masses, where the light quark states have "melted" into a structureless continuum and heavy quark states, which are far fewer in number, can be easily resolved. This is particularly true of the charmonium region. With only eight states in the 0.8 GeV/c^2 region below $D\overline{D}$ and a relatively smooth continuum above, it may be expected that exotics which may exist in the mass region between 3 GeV/c^2 and 5 GeV/c^2 can be resolved and identified unambiguously.

Predictions from hybrids come mainly from calculations based on the bag model, flux tube model, constituent gluon model and recently, with increasing precision, from LQCD [18, 19]. For hybrids the theoretical results agree qualitatively, lending support to the premise that their predicted properties are not too far from reality. Charmonium hybrids can be expected, since the effect of an extra gluonic degree of freedom in meson-like systems is evident in the confining potential for the $c\bar{c}g$ system, e.g., as derived from LQCD calculations in the Born-Oppenheimer approximation [19].

Until now discussions have centered around the lowest-lying charmonium hybrids. Four of these states ($J^{PC} = 1^{--}, 0^{-+}, 1^{-+}, 2^{-+}$) correspond to a $c\bar{c}$ pair with $J^{PC} = 0^{-+}$ or 1^{--} coupled to a gluon in the lightest mode with $J^{PC} = 1^{--}$. The other four states ($J^{PC} = 1^{++}, 0^{+-}, 1^{+-}, 2^{+-}$) with the gluon mode $J^{PC} = 1^{-+}$ are probably somewhat heavier. Three of these eight charmonium hybrids have spin-exotic quantum numbers ($J^{PC} = 0^{+-}, 1^{-+}, 2^{+-}$), so mixing effects with nearby $c\bar{c}$ states are excluded for them, thus making their experimental identification especially easy. Compared to light hybrid candidates, which have reported widths of 200 to 400 MeV [16, 17, 20, 21], charmonium hybrids can be expected to be much narrower, since open charm decays are forbidden or suppressed below the DD^{**} threshold. From experiments at LEAR we know that production rates of such $q\bar{q}$ states are similar to those of states with exotic quantum numbers. We estimate that the cross sections for the formation and production of charmonium hybrids will be similar to those of conventional charmonium states, i.e. of the order of 120 pb [7, 22]. Formation experiments would generate non-exotic charmonium hybrids with high cross sections, while production experiments would yield a charmonium hybrid together with another particle, such as a π or an η. In $\bar{p}p$ annihilation production experiments are the only way to obtain charmonium hybrids with exotic quantum numbers. In the current plan, the first step of exploring charmonium hybrids will consist of production measurements at the highest antiproton energy available ($E_{\bar{p}} = 15\ GeV$, corresponding to $\sqrt{s} = 5.46\ GeV$), in which all available production channels are studied in detail. The next step will consist of formation measurements by means of fine scans in the energy regions in which promising hints of hybrids have been observed in the production measurements.

3.2. Glueballs

LQCD calculations make rather detailed predictions for the glueball mass spectrum in the quenched approximation disregarding quark loops [23]. For example, the calculated width of approximately 100 MeV [24] for the ground state glueball matches the experimental results. In the same mass range that is accessible to $\overline{\text{P}}$ANDA LQCD predicts the presence of about 15 glueballs, some with exotic quantum numbers.

Glueballs with exotic quantum numbers (oddballs) cannot mix with normal mesons: as a consequence, they are predicted to be narrow and easy to identify experimentally [25]. Since the spin structure of an oddball is different, it may very well be that comparing oddball properties with those of non-exotic glueballs will reveal deep insights into the so far unknown glueball structure. The lighest oddball, with $J^{PC} = 2^{+-}$ and a predicted mass of 4.3 GeV/c^2, would be well within the range of $\overline{\text{P}}$ANDA. Like for charmonium hybrids, glueballs can either be formed directly in $\bar{p}p$ annihilation or produced in association with another particle. In either case, the glueball decay to final states like $\phi\phi$ or $\phi\eta$ would be the most favorable reaction below 3.6 GeV/c^2, while for heavier states the preferred decay modes would be $J/\psi\eta$ and $J/\psi\phi$.

It is worth noting that $\bar{p}p$ annihilations present a unique opportunity to search for heavier glueballs. The study of glueballs is a key to understanding long-distance QCD.

4. Hadrons in Nuclear Matter

The investigation of medium modifications of hadrons embedded in hadronic matter is aimed at understanding the origin of hadron masses in the context of spontaneous chiral symmetry breaking in QCD and their modification due to chiral dynamics and partial restoration of chiral symmetry in a hadronic environment. So far, these studies have focussed on the light quark sector. The in-medium potential of pions has been deduced from spectroscopic information obtained in the study of deeply bound pionic states [26]. Study of K meson production in proton-nucleus [27] and heavy-ion collisions [28, 29] are consistent with repulsive and attractive mass shifts for K^+ and K^-, respectively.

A high-intensity $\overline{p}$ beam up to 15 GeV/c will allow to extend these studies to the charm sector for hadrons with hidden or open charm. The short-distance interaction of charmonium states, consisting of charm quarks only, with color singlet hadrons is governed by the exchange of two or more gluons. As the masses of charmonia are dominated by the large mass of the charm quark pair, only little sensitivity to changes in the quark condensate is expected for charmonium states, and the in-medium masses of these states would be affected primarily by a modification of the gluon condensate. Recent calculations indicate small in-medium mass reductions (5-10 MeV/c^2) for the J/ψ and η_c [30], and larger effects for the higher-mass states like the ψ' (≈ 100 MeV/c^2) [31].

D mesons, on the other hand, provide the unique opportunity to study the in-medium dynamics of a system with a single light quark.

To date, very little information is available on charm propagation in nuclear matter, and theoretical predictions are highly model dependent. Therefore, in order to form a basis for a better understanding of the behavior of charmed hadrons in nuclear matter first studies within this program will concentrate on the measurement of J/ψ and D meson production cross sections in $\overline{p}$ annihilation on a series of nuclear targets. Then comparison of the resonant J/ψ yield obtained from $\overline{p}$ annihilation on protons and different nuclear targets allows to reliably deduce the J/ψ-nucleon dissociation cross section [32], which is not only interesting in its own right, but also particularly important for the understanding of J/ψ suppression in ultrarelativistic heavy-ion collisions, interpreted as a signal for a transition to a quark-gluon phase.

Experimentally, the in-medium mass of charmonium states can be reconstructed from their decay into dileptons or photons, whereas D and $\overline{D}$ mesons can be identified via their hadronic decays with $\overline{K}$ and K mesons in the final states.

5. The $\overline{\text{P}}$ANDA detector

The proposed $\overline{\text{P}}$ANDA detector is being designed to study the structure of hadrons in the charmonium mass range as well as the spectroscopy of double hypernuclei. The detector must provide (nearly) full solid angle coverage, it must be able to handle high rates (2×10^7 annihilations/s) with good particle identification and momentum resolution for γ, e, μ, π, K and p. Additional requirements include vertex reconstruction capability and, for charmonium, a pointlike interaction region, efficient lepton identification and excellent calorimetry (both resolution and sensitivity to low-energy photons).

The antiprotons circulating in the HESR hit an internal hydrogen pellet (or jet) target, while for the nuclear target part of the experimental program wire or fiber targets will be used. The detector consists of a target spectrometer (TS) and a Forward Spectrometer (FS).

The TS, for the measurement of particles emitted at laboratory polar angles larger than 5°, is located inside a solenoidal magnet, 2.5 m in length and 0.8 m in inner radius. Its main components are: 4 diamond or silicon start detectors surrounding the interaction region followed by a 5-layer silicon microvertex detector; 15 layers of crossed straw tubes, for the measurement of charged particle trajectories; a cylindrical DIRC and a forward aerogel Čerenkov detector for particle identification; an electromagnetic calorimeter consisting of $PbWO_4$ crystals with Avalanche Photo Diode (APD) readout. The region between the calorimeter and the endcap will be instrumented with 2 sets of mini drift chambers; scintillator strips used for muon identification will be located behind the return yoke of the magnet.

The FS will measure particles emitted at polar angles below 10° in the horizontal and 5° in the vertical direction. It will consist of a dipole magnet with a 1 m gap, with MDCs before and after for charged particle tracking. Particle identification will be achieved by means of a TOF-stop and a dual-radiator RICH detectors. Other components of the FS are an electromagnetc and a hadronic calorimeter followed by a set of muon chambers.

Detailed simulations of the detector concept presented here show its ability to measure electrons, muons, pions, kaons and photons over a large phase space region. Combining a momentum resolution of 1-2 % with a high discriminating power for particle identification and a nearly 4π solid angle coverage allows the application of strong kinematical constraints, which will serve to achieve an excellent level of final state identification and background suppression.

The $\overline{\text{P}}$ANDA project is part of the recently approved new accelarator facility at GSI. The $\overline{\text{P}}$ANDA collaboration currently consists of more than 300 physicists from 48 institutions in 15 countries. The collaboration is now developing a detailed technical proposal for the design and construction of the detector system.

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