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A systematic study of the strong interaction with $\overline{\mathrm{P}}$ANDA

Johan Messchendorp[*] **for the $\overline{\mathrm{P}}$ANDA collaboration**
KVI, University of Groningen, The Netherlands
E-mail: `messchendorp@kvi.nl`

The theory of Quantum Chromo Dynamics (QCD) reproduces the strong interaction at distances much shorter than the size of the nucleon. At larger distance scales, the generation of hadron masses and confinement cannot yet be derived from first principles on basis of QCD. The $\overline{\mathrm{P}}$ANDA experiment at FAIR will address the origin of these phenomena in controlled environments. Beams of antiprotons together with a multi-purpose and compact detection system will provide unique tools to perform studies of the strong interaction. This will be achieved via precision spectroscopy of charmonium and open-charm states, an extensive search for exotic objects such as glueballs and hybrids, in-medium and hypernuclei spectroscopy, and more. An overview is given of the physics program of the $\overline{\mathrm{P}}$ANDA collaboration.

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[*] Speaker.

1. Introduction

The fundamental building blocks of QCD are the quarks which interact with each other by exchanging gluons. QCD is well understood at short-distance scales, much shorter than the size of a nucleon ($< 10^{-15}$ m). In this regime, the basic quark-gluon interaction is sufficiently weak. In fact, many processes at high energies can quantitatively be described by perturbative QCD. Perturbation theory fails when the distance among quarks becomes comparable to the size of the nucleon. As a consequence of the strong coupling, we observe the relatively heavy mass of hadrons, such as protons and neutrons, which is two orders of magnitude larger than the sum of the masses of the individual quarks. This quantitatively yet-unexplained behavior is related to the effect of chiral symmetry breaking.

The physics program of the $\overline{\mathrm{P}}$ANDA (anti-Proton ANnihilation at DArmstadt) collaboration will address various questions related to the strong interactions by employing a multi-purpose detector system [1, 2, 3] at the High Energy Storage Ring for anti-protons (HESR) of the upcoming Facility for Anti-proton and Ion Research (FAIR) [4]. The $\overline{\mathrm{P}}$ANDA collaboration aims to connect the perturbative and the non-perturbative QCD regions, thereby providing insight in the mechanisms of mass generation and confinement. For this purpose, a large part of the program will be devoted to charmonium spectroscopy; gluonic excitations, e.g. hybrids and glueballs; open and hidden charm in nuclei. In addition, various other physics topics will be studied with $\overline{\mathrm{P}}$ANDA such as the hyperon-nucleon and hyperon-hyperon interactions via γ-ray spectroscopy of hypernuclei; CP violation studies exploiting rare decays in the D and/or Λ sectors; studies of the structure of the proton by measuring Generalized Parton Distributions (Drell-Yan and Virtual-Compton Scattering), "spin" structure functions using polarized anti-protons, and electro-magnetic form factors in the time-like region.

2. The experimental facility

The key ingredient for the $\overline{\mathrm{P}}$ANDA physics program is a high-intensity and a high-resolution beam of antiprotons in the momentum range of 1.5 to 15 GeV/c. Such a beam gives access to a center-of-mass energy range from 2.2 to 5.5 GeV/c^2 in $\bar{p}p$ annihilations. In this range, a rich spectrum of hadrons with various quark configurations can be studied. In particular, hadronic states which contain charmed quarks and gluon-rich matter become experimentally accessible.

The $\overline{\mathrm{P}}$ANDA detector will be installed at the High Energy Storage Ring, HESR, at the future Facility for Antiproton and Ion Research, FAIR. FAIR provides a storage ring for beams of phase-space cooled antiprotons with unprecedented quality and intensity [15]. Antiprotons will be transferred to the HESR where internal-target experiments in the beam momentum range of 1.5 – 15 GeV/c can be performed. Electron and stochastic phase space cooling will be available to allow for experiments with either high momentum resolution of about $\sim 10^{-5}$ at reduced luminosity or with high luminosity up to $2{\times}10^{32}$ cm^{-1}s^{-1} with an enlarged momentum spread of $\sim 10^{-4}$.

The $\overline{\mathrm{P}}$ANDA detector is designed as a large acceptance multi-purpose setup. The experiment will use internal targets. It is conceived to use either pellets of frozen H_2 or cluster jet targets for the $\bar{p}p$ reactions, and wire targets for the $\bar{p}A$ reactions.

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To address the different physics topics, the detector needs to cope with a variety of final states and a large range of particle momenta and emission angles. At present, the detector is being designed to handle high rates of 10^7 annihilations/s , with good particle identification and momentum resolution for γ, e, μ, π, K, and p with the ability to measure D, K^0_S, and Λ which decay at displaced vertices. Furthermore, the detector will have an almost 4π detection coverage both for charged particles and photons. This is an essential requirement for an unambiguous partial wave analysis of resonance states. Various design and physics performance studies [16] are ongoing, partly making use of a dedicated computing framework for simulations and data analysis.

3. $\overline{\mathrm{P}}$ANDA physics topics

The level scheme of lower-lying bound $\bar{c}c$ states, charmonium, is very similar to that of positronium. These charmonium states can be described fairly well in terms of heavy-quark potential models. Precision measurements of the mass and width of the charmonium spectrum give, therefore, access to the confinement potential in QCD. Extensive measurements of the masses and widths of the 1^{-} Ψ states have been performed at e^+e^- machines where they can be formed directly via a virtual-photon exchange. Other states, which do not carry the same quantum number as the photon, cannot be populated directly, but only via indirect production mechanisms. This is in contrast to the $\bar{p}p$ reaction, which can form directly excited charmonium states of all quantum numbers. As a result, the resolution in the mass and width of charmonium states is determined by the precision of the phase-space cooled beam momentum distribution and not by the (significantly poorer) detector resolution. The need for such a tool becomes evident by reviewing the many open questions in the charmonium sector. For example, our understanding of the states above the $D\bar{D}$ threshold is very poor and needs to be explored in more detail. Recent experimental evidences (see review [5]) hint at a whole series of surprisingly narrow states with masses and properties which, so-far, cannot be interpreted consistently by theory. Besides the spectroscopy of charmonium states, $\overline{\mathrm{P}}$ANDA will also provide the capability to perform open-charm spectroscopy as the analog of the hydrogen atom in QED (heavy-light system). Striking discrepancies of recently discovered D_{sJ} states by BaBar [6] and CLEO [7] with model calculations have been observed. Precision measurements of the masses and widths of these states using antiprotons and by performing near-threshold scans are needed to shed light on these open problems.

The self-coupling of gluons in strong QCD has an important consequence, namely that QCD predicts hadronic systems consisting of only gluons, glueballs, or bound systems of quark-antiquark pairs with a strong gluon component, hybrids. These systems cannot be categorized as "ordinary" hadrons containing valence $q\bar{q}$ or qqq. The additional degrees of freedom carried by gluons allow glueballs and hybrids to have spin-exotic quantum numbers, J^{PC}, that are forbidden for normal mesons and other fermion-antifermion systems. States with exotic quantum numbers provide the best opportunity to distinguish between gluonic hadrons and $q\bar{q}$ states. Exotic states with conventional quantum numbers can be identified by measuring an overpopulation of the meson spectrum and by comparing properties, like masses, quantum numbers, and decay channels, with - for instance - predictions from Lattice Quantum Chromodynamics (LQCD) calculations. The most promising energy range to discover unambiguously hybrid states and glueballs is in the region of 3-5 GeV/c^2, in which narrow states are expected to be superimposed on a structureless continuum.

In this region, LQCD predicts an exotic 1^{-+} $\bar{c}c$-hybrid state with a mass of 4.2-4.5 GeV/c^2 and a glueball state around 4.5 GeV/c^2 with an exotic quantum number of J^{PC}=0^{+-} [8, 9]. The $\bar{p}p$ production cross section of these exotic states are similar to conventional states and in the order of 100 pb. All other states with ordinary quantum numbers are expected to have cross sections of about 1 μb.

One of the challenges in nuclear physics is to study the properties of hadrons and the modification of these properties when the hadron is embedded in a nuclear many-body system. Only recently it became experimentally evident that the properties of mesons, such as masses of π, K, and ω mesons, change in a dense environment [10, 11, 12, 13]. The $\overline{\text{P}}$ANDA experiment provides a unique possibility to extend these studies towards the heavy-quark sector by exploiting the $\bar{p}A$ reaction. For instance, an in-medium modification of the mass of the D meson would imply a modification of the energy threshold for the production of D mesons, compared to a free mass. In addition, a lowering of the D-meson mass could cause charmonium states which lie just below the $D\bar{D}$ threshold for the $\bar{p}p$ channel to reside above the threshold for the $\bar{p}A$ reaction. In such a case, the width of the charmonium state will drastically increase, which can experimentally be verified. Although this is intuitively a simple picture, in practice the situation is more complicated since the mass of various charmonium states might also change inside the nuclear medium. Besides the indirect in-medium studies as described above, $\overline{\text{P}}$ANDA will be capable to directly measure the in-medium spectral shape of charmonium states. This can be achieved by measuring the invariant mass of the di-lepton decay products. For the $\Psi(3770)$, for instance, models predict mass shifts of the order of –100 MeV [14], which are experimentally feasible to observe.

So far, this paper has concentrated on only a few of the topics which will be addressed by the $\overline{\text{P}}$ANDA collaboration. There exists, however, a large variety of other physics topics which can ideally be studied with the $\overline{\text{P}}$ANDA setup at the antiproton facility at FAIR. For example, there is growing interest within the $\overline{\text{P}}$ANDA collaboration to make use of electro-magnetic probes, photons and leptons, in antiproton-proton annihilation. These probes will be used to study the structure of the proton by measuring Generalized Parton Distributions (GPDs), to determine quark distribution functions via Drell-Yan processes, and to obtain time-like electro-magnetic form factors by exploiting the $\bar{p}p \rightarrow e^+e^-$ reaction with an intermediate massive virtual photon. Furthermore, the $\overline{\text{P}}$ANDA collaboration has the ambition to perform hypernuclei experiments, which enables a study of the hyperon-nucleon and hyperon-hyperon interactions. Finally, plans for symmetry violation experiments with $\overline{\text{P}}$ANDA will open a window onto physics beyond the Standard Model of particle physics.

4. Summary

The $\overline{\text{P}}$ANDA experiment at FAIR will address a wide range of topics in the field of QCD, of which only a small part could be presented in this paper. The physics program will be conducted by using beams of antiprotons together with a multi-purpose detection system, which enables experiments with high luminosities and precision resolution. This combination provides unique possibilities to study hadron matter via precision spectroscopy of the charmonium system and the discovery of new hadronic matter, such as charmed hybrids or glueballs, as well as by measuring the properties of hadronic particles in dense environments. New insights in the structure of the proton will be obtained by exploiting electromagnetic probes. Furthermore, the next generation of hypernuclei spectroscopy will be conducted by the $\overline{\mathrm{P}}$ANDA collaboration and at the J-PARC facility in Japan. To summarize, $\overline{\mathrm{P}}$ANDA has the ambition to provide valuable and new insights in the field of hadron physics which would bridge our present knowledge obtained in the field of perturbative QCD with that of non-perturbative QCD and nuclear structure.

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