Hadron physics at FAIR - the PANDA antiproton experiment

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The planned PANDA experiment belongs to the group of core experiments at the new FAIR facility in Darmstadt/Germany. PANDA will be a universal detector to study the strong interaction by utilizing the annihilation process of antiprotons with protons and nuclear matter. The current paper gives an introduction into part of the planned physics program.

1 Introduction

In the so-called Standard Model of particle physics quarks and leptons are considered to be the elementary building blocks of matter. Matter thus manifests itself in a hierarchy of composite systems. The stability of each system is determined by the interaction among the respective constituents. Hadron Physics is the physics of strongly interacting systems. In the past thirty years quantum chromodynamics (QCD) has evolved as the theory of strong interactions that describes the interaction among the fundamental quarks through the exchange of gluons. QCD is believed to be well understood at short distance scales, but this is no longer the case as soon as the basic quark-gluon coupling is no longer weak. This region of strong QCD is governed by non-perturbative phenomena leading, e.g., to the formations of hadrons. The underlying processes like confinement and chiral symmetry breaking are however not very well understood. This presents a profound intellectual challenge for both experimentalists and theorists. Experiments with antiprotons have proven in the past to be a rich source of information in hadron physics. With the new proposed high-energy storage ring HESR for antiprotons at the future FAIR facility in

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Darmstadt, the physics of strange and charm quarks studied by antiproton annihilations will be accessible for hadron physics. This region is exactly the transition region between the perturbative QCD at short scales and strong QCD.

The availability of cooled antiproton beams with momenta up to 15 GeV/c will provide a broad research program that includes among others:

- search for gluonic degrees of freedom, e.g., hybrids and glueballs
- spectroscopy of charmonium states
- spectroscopy of hypernuclei and double hypernuclei.

This paper will describe the physics motivation, the parameters envisioned for the HESR and the planned PANDA detector.

2 Gluonic Degrees of Freedom

Hadron spectroscopy is the basis that inspired the SU(3) quark model and QCD as the generally accepted theory of strong interactions. QCD is a non-Abelian gauge theory and as a consequence, the gauge bosons, the gluons, can interact with each other. Therefore QCD predicts the existence of bound states of gluons, called glueballs (gg, ggg). Other types of hadronic matter in which gluons contribute to the overall quantum numbers, called hybrids ($q\bar{q}g$), could also exist. The gluonic excitation in a hybrid leads to new J^{PC} quantum numbers for this state, where J denotes the total angular momentum of the resonance, P its parity and C its charge conjugation. Some J^{PC} combinations cannot be formed by the fermion-antifermion system $q\bar{q}$, so their observation would be the cleanest experimental evidence for a non-$q\bar{q}$ state. In any case, the precise measurement of the properties of several glueball or hybrid states compared to $q\bar{q}$ mesons would help us understand QCD in the non-perturbative regime.

Why is it so important to find the gluonic degrees of freedom? The elementary particles of the Standard Model gain their mass through the Higgs mechanism. However, only a few percent of the mass of the proton is due to the Higgs mechanism. The rest is created in an unknown way by the strong interaction. Glueballs would be massless without the strong interaction and their predicted masses arise solely from the strong interaction. The possibility to study a whole spectrum of glueballs might therefore be the key to understanding the mass creation by the strong interaction. What are the results in this field so far?

The most prominent reactions to study gluonic degrees of freedom are radiative J/ψ decays, central production processes, and antiproton-proton annihilation. Because of the existence of LEAR at CERN, antinucleon-nucleon ($N\bar{N}$) annihilation data now dominate.

The study of $\bar{p}p$ annihilation has been underway for the past thirty years. Several bubble chamber experiments at CERN and BNL first investigated this topic. In 1983, with the low energy antiproton ring (LEAR) at CERN, a unique facility for antiproton physics came into operation. Until its closure at the end of 1996, LEAR provided pure and high-intensity antiproton beams (up to 2×10^6 $\bar{p}$/s) in the momentum range between

60 and 1940 MeV/c with a small momentum spread of $\Delta p/p \sim 10^{-3}$. The second generation of LEAR experiments was comprised of high-statistics 4π experiments for charged and neutral particles. This turned out to be the key to finding gluonic degrees of freedom. Not only was the most promising glueball groundstate candidate ($J^{\mathrm{PC}}=0^{++}$), the $f_0(1500)$, discovered in $\bar{\mathrm{p}}\mathrm{p}$ annihilations[1], but also two states with exotic quantum numbers ($J^{\mathrm{PC}}=1^{-+}$) are unambiguously seen[2, 3, 4]. Because their quantum numbers are exotic, those two particles cannot be ordinary mesons. What is especially striking in $\bar{\mathrm{p}}\mathrm{p}$ annihilations is the fact that these exotic particles are produced with the same strength as ordinary mesons. It therefore seems that the gluon richness of the annihilation process makes $\bar{\mathrm{p}}\mathrm{p}$ annihilations the prime search ground for gluonic excitations. Unfortunately the energy range of the LEAR machine was limited and therefore, e.g., higher-mass glueballs were out of reach. The majority of them are predicted by lattice calculations to have a mass between 3 and 5 GeV/c^2 [5]. Because of this high mass, most of them are not accessible for radiative J/ψ decays and central-production processes, and a new antiproton machine seems to be the only chance to find them and study their properties.

Charmonium hybrids ($c\bar{c}g$) are predicted above 4 GeV/c^2. The ground state has exotic quantum numbers ($J^{\mathrm{PC}}=1^{-+}$) and is expected to be rather narrow. Lattice calculations predict its most-favored decay mode to be $\chi + (\pi^0\pi^0)_{\mathrm{S-wave}}$[6, 7]. The appearance of the charmonium state in the decay channel facilitates the detection in experiments.

3 Charmonium Spectroscopy

The best understanding of charmonium has been achieved for the ψ states. These can be formed directly at electron-positron colliders. With an antiproton beam, however, charmonium states of all quantum numbers can be formed directly. A scan with varying beam energy through the charmonium resonance allows its precise width determination. The precision of the mass and width measurement depends solely on the beam quality, putting less demands the detector resolution. This has been demonstrated by the excellent results achieved by the Fermilab experiments E760/835.

Potential models for $\mathrm{q}\bar{\mathrm{q}}$ interactions are tuned to the results of charmonium spectroscopy. The Fermilab experiments E760 and E835 showed that cooled antiproton beams are extremely well suited to do precision charmonium spectroscopy. In fact, the vast majority of high-precision charmonium data were measured in $\bar{\mathrm{p}}\mathrm{p}$ reactions[8]. Since Fermilab now concentrates all resources on finding the Higgs particle, the E835 experiment was shut down, leaving many important questions unanswered. Among them are:

- the precise mass and the width of the ground state η_c
- the mass and properties of the first radial excitation of the η_c
- the precise mass and the properties of the h_c resonance of the charmonium system
- radiative transitions of the χ_J charmonium states
- missing charmonium states above the $\mathrm{D}\bar{\mathrm{D}}$ threshold.

In particular charmonium states with quantum numbers different from $J^{PC}=1^{--}$ are best studied with antiproton annihilations, while those with $J^{PC}=1^{--}$ states will be studied intensively with the CLEOc and BES experiments. Antiproton annihilations allow formation experiments for all charmonium states.

4 Hypernuclear Spectroscopy

A hypernucleus contains one or more hyperons implanted into the nuclear medium and therefore adds a third dimension (strangeness) to the nuclear chart. Previous experiments in this field suffered from very low statistics and the limited detector resolution of the magnetic spectrometers used. But precisely one of the goals of hypernuclear physics is to determine as accurately as possible the level spectra and decay properties of (multi)strange hypernuclei. The combination of a high-luminosity antiproton storage ring with a modern detector system, consisting of novel solid-state micro trackers in connection with a high resolution γ spectrometer, will remove the present obstacles to hypernuclear spectroscopy.

The experimental concept foresees the production of baryon-antibaryon pairs inside nuclear matter. The antibaryon (e.g., a $\bar{\Xi}$) could serve as a trigger for the reaction while the baryon (in this case a Ξ^-) is slowed down inside the nucleus and subsequently absorbed in a secondary active target. This capture reaction will then lead to the production of $\Lambda\Lambda$ hypernuclei. A modern highly segmented Ge-array detector will surround this target and allow high-precision spectroscopy of these double hypernuclei. The expected rates for the HESR experiments are approximately 300000 stopped Ξ^- per day, and with the typical γ branching ratios and detection efficiencies, one will observe several hundred γ transitions per day.

5 Further Physics Possibilities

The annihilation of antiprotons with a nucleon inside a nucleus allows the production of charmonium inside nuclear matter. If this charmonium decays into open-charm particles e.g. the interaction of the different D mesons inside nuclear matter can be studied. The availability of antiprotons at FAIR will allow for production studies of baryon-antibaryon pairs up to charmed baryons. The antiproton beams could be used to study the inverted deeply virtual and wide-angle Compton scattering process, or allow the study of D meson decays. The search for CP violation in the charm sector could be envisaged. There are as well thoughts on how to implement polarization into the whole complex allowing for single spin experiments with PANDA.

6 The Antiproton Accelerator Complex

The FAIR facility foresees the installation of several new accelerator rings. The 30 GeV protons from the SIS100 could be used to produce antiprotons that are subsequently collected, stored and cooled in two smaller storage rings. Those pre-cooled antiprotons are then transferred via the SIS100 into a dedicated antiproton storage ring called HESR. The

HESR is equipped with one internal target station. The HESR will provide antiprotons with momenta between 1.5 and 15 GeV/c, giving a center-of-mass energy of up to 5.5 GeV. The beam will be stochastically cooled over the whole momentum range, giving a beam momentum spread of δp/p = 10^{-4}. For the high-precision charmonium spectroscopy, additional high-energy electron cooling for momenta up to 8 GeV/c is foreseen. The momentum spread with this additional electron cooling is δp/p = 10^{-5} in a high resolution mode of the storage ring operation. The antiproton program is only part of the whole proposed FAIR complex. However, the accelerator complex is optimized for a maximum parallel operation between the antiproton physics program and the other physics programs, to make best use of the facility.

7 The PANDA Detector

Most of the experimental program will be done with a general-purpose detector, which is currently being designed by the PANDA group consisting of 47 institutions worldwide.

To achieve the physics aims, the detector needs to cover the full solid angle. Good particle identification and excellent energy and angular resolution for charged particles and photons are mandatory. Charm particles decay often lead to di-lepton pairs. Thus, muon detection capabilities and a highly-segmented low-threshold electromagnetic calorimeter are important to tag and precisely reconstruct hidden-charm and to reduce background. Good vertex recognition and particle identification for charged kaons from very low energies up to a few GeV is required to reconstruct light hadronic and open-charm final states. At the same time, the detector must withstand large radiation dosage from hadrons emitted by the spallation process when using nuclear targets. These spallation products include neutrons down to thermal energies, which contribute most.

The planned PANDA detector is subdivided into two parts: i) a targets spectrometer with a solenoid magnet surrounding the interaction region and ii) a forward spectrometer with a large-acceptance dipole magnet. The dipole magnet in forward direction bends as well the HESR beam, allowing for an electromagnetic calorimeter to be placed in 0° direction. Only this combination of two spectrometers therefore allows a full angular coverage and takes into account the wide range of energies. At the same time it still has sufficient flexibility, so that individual components can be exchanged or added for specific experiments, e.g. for the experiments with hypernuclei or for the special needs of CP violation studies.

The internal target, which could be a pellet target of frozen hydrogen droplets, a gas jet target or a wire used as nuclear target, is surrounded by Si-pixel detectors in the vertex region. The main vertex tracking further out is done with straw chambers or a high-rate TPC and mini drift chambers. Ring imaging Cherenkov counters will provide the particle identification. The proposed electromagnetic calorimeter is an arrangement of $PbWO_4$ crystals, read out by avalanche photodiodes. The superconducting solenoid provides a field of 2 T. Particles emitted with polar angles below 10° in the horizontal and 5° in the vertical direction are measured with the help of a 1 m gap dipole. Mini drift chambers will be located before and behind the dipole for tracking. Particle identification will be obtained by a TOF-Stop detector and a dual-radiator RICH detector. Behind this there is a $\sim 3\,\mathrm{m}^2$ electromagnetic calorimeter and a hadronic calorimeter followed by a muon detection system.

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More detailed information about PANDA can be found at: http://www.gsi.de/panda