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PANDA: Strong Interaction Studies with Antiprotons

The Antiproton Anihilation in Darmstadt (PANDA) collaboration at the Facility for Antiproton and Ion Research (FAIR) is a cooperation of more than 400 scientists from 19 countries.

FAIR will be an accelerator facility leading the European research in nuclear and hadron physics in the coming decade. It will address a wide range of physics topics in the fields of nuclear structure, nuclear matter, atomic, and plasma physics. Several topics in applied science and accelerator development will be addressed as well. FAIR builds on the experience and technological developments from the existing GSI facility, and incorporates new technological concepts, such as rapidly cycling super-conducting magnets.

The existing GSI accelerators will be upgraded and complemented by a proton-linac to be used as injectors for the newly built complex of synchrotrons and storage rings to form FAIR. This facility will provide intense secondary beams of antiprotons and rare isotopes, which will be used for the research at the experimental setups.

It is sometimes said that the whole is more than the sum of its parts. For the proton, this expression is literally true. The sum of the masses of its valence quarks account for less than 2% of the proton's total mass, with the rest resulting from the kinetic and binding energies among quarks due to dynamics of the strong interaction. The accepted theory of the strong interaction is quantum chromodynamics (QCD). It describes the properties of quarks and their interactions through gluons, the force mediator of the strong interaction. QCD is very successful in predicting processes at high ener-

gies where the coupling constant α_s is small and perturbation theory is applicable. However, at low energies, the theory becomes strongly coupled as α_s becomes large. In this non-perturbative regime, it is still hard to make predictions from first principles. Furthermore, complex systems of quarks and gluons are strongly coupled many-body problems.

The complexity of many-body systems in non-perturbative QCD gives rise to many questions: What are the effective degrees of freedom that systematically describe resonances and bound states? Where are the exotic resonances and bound states predicted by QCD? How do bound quark systems interact? What is the residual structure of the hadronic systems? Thus, the central goal of the PANDA experiment is the elementary understanding of hadrons using the power of an antiproton beam on hydrogen or nuclear targets.

The annihilation of antiprotons has proven in the past to be a universal tool for carrying out such investiga-

tions. Open and hidden charm, lepton pairs and radiative channels, hidden strangeness and hyperons, are commensurable probes to explore the imminent questions among bound states of QCD.

“Why antiprotons?” is asked frequently. The answer lies in the advantages antiprotons have in the production of a rich variety of hadrons with respect to other experimental probes and the flavor-blindness of the well-defined initial states, which is complemented by the unique feature of high precision mass scanning.

An important feature of the new antiproton facility is the combination of phase-space cooled beams and dense internal targets, comprising challenging beam parameters in two operation modes: a high-luminosity mode with beam intensities up to 10^{11} in a later stage, and a high-resolution mode with a momentum spread down to a few times 10^{-5} and beam intensities up to 10^{10} . A powerful stochastic cooling system will be employed to meet the experimental requirements. The High

Figure 1. High Energy Storage Ring at FAIR. The PANDA detector is located in one of the straight sections where the antiproton beam interacts with a fixed target.

Figure 2. Some of the many accessible hadron species with PANDA and HESR.

Energy Storage Ring (HESR) is filled by the Collector Ring (CR), which accumulates by stacking the antiprotons every 10 seconds from the collision of 2.5×10^{13} protons of 29 GeV in a 50 ns bunch on the production target.

The HESR lattice is designed as a racetrack-shaped ring, consisting of two 180° arc sections connected by two long straight sections. One straight section will mainly be occupied by an electron cooler at a later stage and will host smaller experiments for nuclear and atomic physics with ion beams. The other section will host RF cavities, injection kickers, septa (Figure 1), and the installation of the PANDA experiment with an internal target. For stochastic cooling, pickup and kicker tanks are located in the straight sections, opposite to each other. The momentum of the antiprotons ranges from 1.5 to 15 GeV/c , allowing for a wide variety of physics channels (Figure 2).

The PANDA experiment belongs to the third generation of hadron physics experiments, hereby building on the

experiences and successes of previous generations.

The availability of accelerators and detectors like the bubble chambers led to a prosperous time in particle physics in the 1950s and 1960s with the discovery of many new particles. The vast majority of these particles came to be understood, at least qualitatively,

due to the pioneering work of Gell-Mann as being composed of quarks that interact with each other via the exchange of gluons. Baryons are hadrons consisting of three quarks, and mesons are hadrons consisting of an antiquark–quark pair.

The field of hadron physics was fragmented over decades, according to the questions under investigation and subject to the methods and tools used, into the branches of spectroscopy, structure, and interactions of hadrons.

While specialized experiments have been dedicated to each of those subfields over the past 20 years, the PANDA experiment has been especially designed together with the accelerator to address open and burning questions from all the subfields and beyond.

The PANDA experiment features a modern multipurpose detector (Figure 3). The combination of a high-quality antiproton beam at the HESR, an unprecedented annihilation rate, and a sophisticated event filtering, is an ideal experimental infrastructure to address important questions to all aspects of this field by collecting large statistics and high-quality exclusive data to test

Figure 3. CAD drawing of the PANDA detector, currently under construction and to be completed and commissioned in 2024.

Figure 4. High antihyperon–hyperon production cross-sections in antiproton–proton annihilations.

QCD in the non-perturbative regime. In the following, we will outline a few of the physics aspects that will be addressed using this facility (see Refs. [1, 2] for more details).

PANDA will copiously produce antihyperon–hyperon pairs through the reaction $\bar{p}p \rightarrow Y\bar{Y}$. The energy scale is given by the mass of the strange quark ($m_s \sim 100 \text{ MeV}/c^2$), which is below, but near the strong coupling scale Λ_{QCD} . This corresponds to the confinement domain, where our knowledge of the strong interaction is scarce. Therefore, the relevant degrees of freedom—quarks and gluons or hadrons—remain unclear. Spin observables have been proven to be very sensitive to the underlying degrees of freedom of the model describing the interaction. The high cross-section for hyperon pair production using antiproton interactions (see Figure 4) will provide the necessary high statistics to access spin observables with sufficient precision. In addition, so far unmeasured multi-strange hyperons are accessible with PANDA. In particular, seven polarization parameters of the spin 3/2 Ω hyperon can be extracted for the first time.

This large production cross-section will also enable several innovative studies of systems containing two or even more units of (anti)strangeness in antiproton–nucleus collisions at the PANDA experiment. The interaction

of antibaryons in nuclei provides a unique opportunity to elucidate strong in-medium effects in baryonic systems. Quantitative information on the antihyperon potentials will be obtained for the first time via exclusive antihyperon–hyperon pair production close to its production threshold in antiproton–nucleus interactions. After pioneering studies of the Λ potential during the first phase of PANDA, the Ξ and even the Ω potential can be explored once the full luminosity is available. Baryons with strangeness embedded in the nuclear environment, hypernuclei, or hyperatoms, are the only available tool to approach the many-body aspect of the three-flavor strong interaction. As an example, high resolution γ -spectroscopy of excited states in several doubly strange $\Lambda\Lambda$ -hypernuclei will be performed for the first time. Hypernuclear studies would result also in valuable insights to astrophysics as well, such as the Hyperon-puzzle of neutron stars and mechanisms of core-collapse supernovae.

The field of charmonium spectroscopy is an exciting field with many discoveries in the past 15 years. Many predicted states have not been observed and, on the other hand, masses, widths, and decay rates of many unexpected states (XYZ states) have been measured. Until today, a coherent picture cannot be drawn from what is available experimentally. PANDA will

contribute to this field in two unique ways: (a) in explorative studies in many-body experiments to search for high-spin and spin-exotic states and (b) by a precision measurement of the mass and width (or more generally the line-shapes) of any neutral charmonium-like state. The very small momentum spread of the antiproton beam allows a determination of the width, for example of the $X(3872)$, with an accuracy of 50 keV. Such an accuracy will provide a decisive measurement on the nature of the narrow $X(3872)$. This technique can also be used to investigate excitation curves of open-charm final states, like, for example, $D_s D_{s0}^*(2317)$ to measure the width of the respective $D_{s0}^*(2317)$.

Furthermore, antiproton annihilations allow for the study of a rich variety of nucleon structure observables in large (partly) unexplored areas such as the kinematical regime that corresponds to the time-like (positive, s-channel) momentum transfer of the virtual photon. The electromagnetic form factors of the proton, transition distribution amplitudes (TDA), wide angle compton scattering (WACS), and Drell-Yan processes for accessing transition momentum-dependent parton-distribution functions (TMD-PDF) are examples of those variables. Figure 5 shows how crossing symmetry, for example, connects space- and time-like regions.

The main objectives of the design of the PANDA experiment are to achieve almost 4π acceptance, high resolution for tracking, particle identification and calorimetry, high-rate capabilities, and a versatile readout and event selection. To obtain a good momentum resolution, the detector will be composed of two magnetic spectrometers: the Target Spectrometer (TS), based on a superconducting solenoid magnet surrounding the interaction point, for particle tracks at large angles and the

Figure 5. Crossing symmetry relates electromagnetic scattering off the proton to, for example, lepton and photon pair production from antiproton-proton annihilations (elm FF = electromagnetic form-factor, GPD = generalized parton distribution, GDA = generalized distribution amplitudes, M_h = hard process amplitude, DA = distribution amplitude, see Refs. [1, 3] for more details).

Forward Spectrometer (FS), based on a dipole magnet, for small angle tracks. In both spectrometer parts, tracking, charged-particle identification, electromagnetic calorimetry, and muon identification will be available to allow detection of the complete spectrum of final states relevant for the PANDA physics objectives.

The TS has a typical onion-like structure, very much like the detectors used for the B-Factories Babar and Belle: A cluster jet or pellet target system will be used to provide either a cluster beam of a target gas or frozen hydrogen pellets. Thin foils or noble gasses will be used for antiproton-nucleus studies. The interaction point is surrounded by the Micro Vertex Detector (MVD) which has a vertex resolution of about 50 μm in transverse and 100 μm along the beam direction. Surrounding the MVD, the Straw Tube Tracker and Gas Electron Multiplier (GEM) stations will be used for tracking charged particles ($\Delta p_T/p_T = 1.2\%$) in the magnetic field. Photons and the energy of electrons will be reconstructed with the Electromagnetic Calorimeter (EMC). The EMC consists of a barrel (azimuthal angle 22° to 140°), a forward endcap (down to the opening for the FS) and backward

endcap (145° to 170°) and consists of about 16,000 PbWO_4 crystals providing an energy resolution of $1.5\%/\sqrt{E}$, whereby E is given in units of GeV. Particle identification of pions, kaons, and protons will utilize information from a time-of-flight system (ToF), a cylindrical Detection of Internally Reflected Cherenkov (DIRC) light, and a forward Disc DIRC detector. The ToF will use scintillating tiles with Silicon Photomultiplier readout. The cylindrical DIRC is a bar-type DIRC with quartz-prisms, while the Disc DIRC uses large quartz plates. The solenoid magnet will provide a homogeneous magnetic field up to 2 T in the beam direction. The segmented yoke is instrumented with chambers for muon identification.

The FS covers polar angles below 10° horizontally and 5° vertically. Charged particles will be detected using the Forward Tracking System, which consists of multiple straw tube layers, in conjunction with a dipole magnet with variable field depending on the incident antiproton momentum. The momentum resolution for tracks above 1 GeV/c is better than 1%. A Forward ToF and an aerogel-based Ring Imaging Cherenkov Counter detector will provide particle identi-

fication. A Shashlyk-type calorimeter with an energy resolution of $3\%/\sqrt{E}$ is followed by the Muon Range System for muon detection. At the forward end, the Luminosity Detector uses elastic scattering of antiprotons on protons to determine the interaction rate measuring antiprotons deflected at low angles. A detailed description of the PANDA detector and its components can be found at Ref. [4].

As the detector response of background events is very similar to that of the decay of the exotic states, the use of a conventional triggered readout scheme, where a limited number of subdetectors generates a trigger signal that engages the readout of the complete detector, is not practical. Therefore, a new type of intelligent readout is being developed, where kinematical constraints are imposed online on reconstructed events. This technique is dubbed as “triggerless readout” and allows adjusting the data selection to numerous physics channels. A data reduction factor of up to $\sim 10^3$ is expected to be achieved by employing this technique for the whole detector, resulting in a data rate of $\sim 10^4$ events/s (or, equivalently, 200 MB/s) that will then be sent to storage for offline processing and analysis.

Besides the foreseen advances in detector technology and data treatment, also the theoretical developments that go hand-in-hand with the experimental developments will lead to new and deep insights into the dynamics of the strong interaction. The insights that PANDA will gain in the field of QCD might have far-reaching implications to other fields of physics as well, in particular for those in which similar non-perturbative phenomena take place (wide range reaching from string theory to weather phenomena). The study of non-perturbative phenomena in a systematic way is feasible only in hadron physics. This supplements the long list of features that can be addressed with PANDA.

GSI has a distinguished history of having made important contributions to the physics of the strong interaction, in particular in the field nuclear physics. FAIR will be built on these foundations and the proposed PANDA experiment plays a complementary role, providing a link between nuclear and hadron physics. The construction of the PANDA detector has started and *in-situ* commissioning of the initial setup is scheduled for 2024, while early physics with an antiproton beam is expected in 2025.

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