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NUCLEAR AND HADRON PHYSICS WITH ANTIPROTONS: PANDA@FAIR

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Abstract

The future Facility for Antiproton and Ion Research (FAIR) at the GSI Darmstadt, Germany, comprises an experimental program with high quality and high intensity antiproton beams in the momentum range from 1.5 to 15 GeV/c. PANDA (Antiproton Annihilation at Darmstadt) is a dedicated experiment to study antiproton annihilations on protons and nuclei.

This article gives an overview on the experimental facility, the physics program with special emphasis on the nuclear physics topics, and the status of the detector design.

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Introduction

At the Gesellschaft für Schwerionenforschung (GSI) [1] in Darmstadt, Germany, a new facility is currently designed and built. The Facility for Antiproton and Ion Research (FAIR) [2] comprises a new possibility for GSI: the production of secondary antiproton beams. This species of beams could be exploited by several experiments, the first one, which was present already at the early stage of the project [3], is PANDA (antiproton annihilation at Darmstadt) [4].

The Facility

This section describes the part of the facility particularly with regard to PANDA; details about the full facility can be found in [2,3]. To produce the antiproton beams, a primary beam of protons will be used. Therefore, a new proton linear accelerator will be built, which injects the protons in a first synchrotron ring (the existing, upgraded SIS), followed by the acceleration to the energy of 30 GeV in the new SIS100. An intensity of several 10^{13} protons per second is envisaged. These protons hit a production target, and the produced secondary antiprotons will be accumulated and cooled using two subsequent storage rings. Then the antiprotons will be accelerated in the SIS100 to the desired energy from the experiment, and finally injected in the High Energy Storage Ring (HESR), where the experiment will be located. Another possibility which is considered foresees to omit the acceleration in the SIS100 but rather transfer the antiprotons at a fixed energy into HESR, where the acceleration/deceleration will be done, applying a synchrotron operation mode to the ring.

The HESR, a 15 Tm ring, should provide antiprotons in the momentum range from 1.5 to 15 GeV/c. The design luminosity is $2 \cdot 10^{32}$ cm^{-2}s^{-1}. The ring will be equipped with electron cooling (for lower beam momenta) and stochastic cooling to ensure excellent beam quality. For the so-called high precision mode, a momentum spread of $\leq 10^{-5}$ should be yielded, whereas at design luminosity this condition is relaxed by a factor ≈ 10.

PANDA will operate as a fixed internal target experiment at HESR.

Overview: The Physics Program

Figure 1 shows in an overview the mass range to be exploited by PANDA with antiproton annihilations on a proton target in the above mentioned antiproton momentum range. The maximum antiproton momenta of previous experiments at CERN (LEAR) and FNAL (E760/E835) are indicated below.

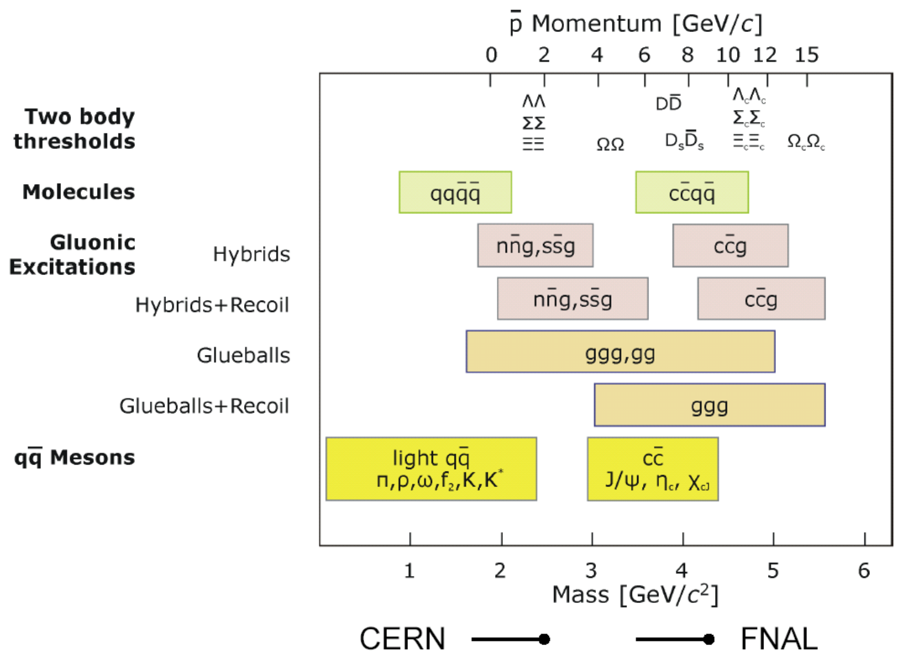

Figure 1:

PANDA will take data in an energy range which corresponds to a transition region between perturbative and non-perturbative QCD – this is characterized having the hadrons as relevant degrees of freedom, and the confinement of quarks; the fact that the mass of the observed hadrons is much bigger than the sum of the bare quark masses plays a crucial role together with the self-interaction among the gluons.
To shed light on these phenomena, PANDA will investigate the following main topics:

- Spectroscopy of Charmonium
- Search for Glueballs and Hybrids
- Charm in Nuclei
- Double Λ Hypernuclei

Additional topics are also included in the research program:

– D-meson spectroscopy (e.g. rare decays),
– CP-violation (D-mesons, $\Lambda\bar{\Lambda}$),
– Generalized Parton Distributions ($\bar{\text{p}}$p$\rightarrow \gamma\gamma$),
– Transversity (asymmetries in Drell-Yan $\bar{\text{p}}$p$\rightarrow \mu^+\mu^-$),
– The timelike electromagnetic form factor of the proton,
– ...

Hadron Physics

Charmonium Spectrocopy

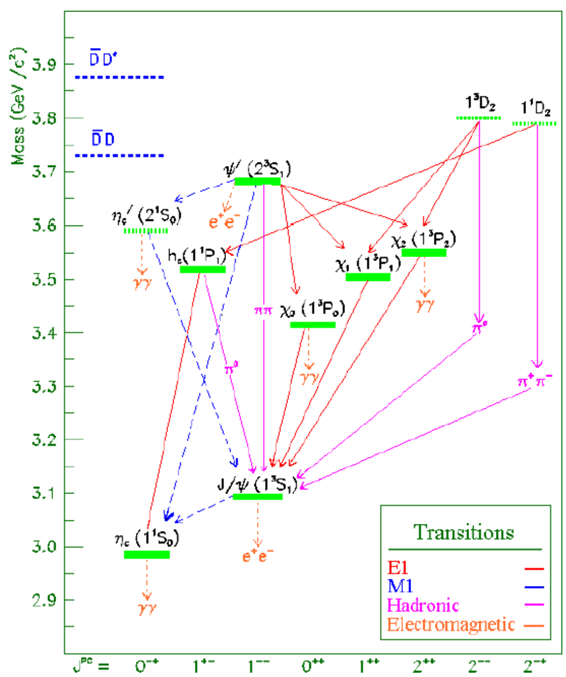

Figure 2:

Figure 2 shows the mass spectrum of the charmonium states as a function of their quantum number. The transitions are indicated by the arrows, the dashed blue horizontal lines show the threshold for the free decay in D-mesons.

PANDA will persue a systematic study of the complete spectrum with high statistics and high precision. Especially, open questions like the width of the h_c state, the establishment of the states above the D$\bar{\text{D}}$ threshold, and radiative deexcitation modes, will be studied.

Since PANDA will make use of the $\bar{\text{p}}$p reaction, the direct formation of all states in the spectrum is possible, whereas for experiments at e^+e^- colliders the formation is restricted to the quantum numbers of the virtual photon. This means also that a resonce scan for all the states is only limited to the momentum resolution of the antiproton beam.

Glueballs and Hybrids

QCD predicts, besides the ordinary states, also the existence of objects like glueballs (formed by gluons) and hybrids (formed by quarks and gluons). Glueballs have been searched for quite some time in the light quark sector, there are candidates (like the $f_0(1500)$), but the mixing with other states in that mass region makes it difficult to perform an unique identification.

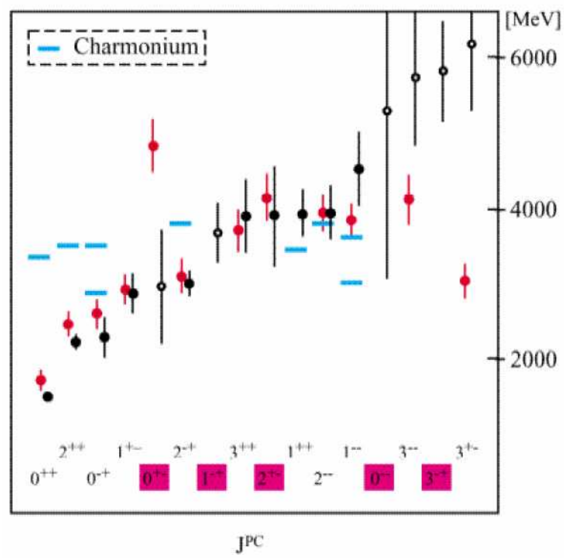

Figure 3:

PANDA will accomplish dedicated experiments for the search for glueballs and hybrids in the charm quark mass region. In Figure 3, predictions for glueball states (red dots [6], black dots [7], here, the error bars indicate the predicted width) together with the charmonium states (blue lines) are shown. The quantum numbers underlayed with color are exotic quantum numbers, which do not appear for pure $q\bar{q}$ states. The observation of a state with exotic quantum numbers hence will be a clean signature for a non-conventional state. Furthermore, the mixing with other states might be not that pronounced as in the light quark range (less states, smaller widths). For the charmed hybrids, the situation is similar, there are predicitons from lattice QCD, e.g. [8]. Also here, some states have exotic quantum numbers.

Nuclear Physics

Charm in Nuclei

The systematic study of the properties of charmed mesons (D) and charmonium ($c\overline{c}$) in nuclear matter ($\rho = \rho_0$) will be done for the first time with PANDA.

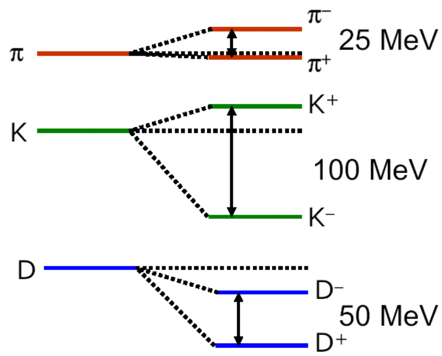

Figure 4:

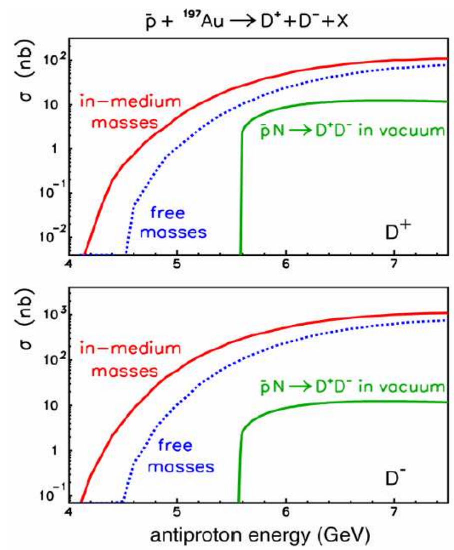

Figure 5:

In the light quark sector, there is evidence for a mass modification and a mass splitting between the different charges for pions [9] and kaons [10] in the nuclear medium. This phenomenon might be due to a (partial) restoration of the chiral symmetry in nuclear matter. Figure 4 shows schematically the effect going from $\rho = 0$ (left) to $\rho = \rho_0$ (right).

For the D-mesons a theory prediction [11] is shown; one might expect also a mass shift and a mass splitting in the D-meson system. In Figure 5 a calculation [12] of the cross sections for D^- (below) and D^+ (above) in the annihilation of an antiproton on a ^{197}Au nucleus is shown.

In analogy to the $K^\pm$ production, an enhanced production yield with respect to the elementary process (green line, $\bar{p}N$) is predicted as well as different yields for D^+ and D^-. The experimental strategy for these measurements would be the study of the $D^\pm$ production as a function of the $\bar{p}$ momentum and the mass number A of the target nucleus. Experimental consequences of a possible $D\bar{D}$ attractive mass shift are shown in Figure 6. Under the assumption of a small mass shift of the $c\bar{c}$ states, a lowered $D\bar{D}$ threshold would yield to an increased phase space for the decay in $D\bar{D}$, for states like the ψ(3770) it will open a $D\bar{D}$ decay branch, resulting in an increased width and a decrease of the branching ratio in dileptons.

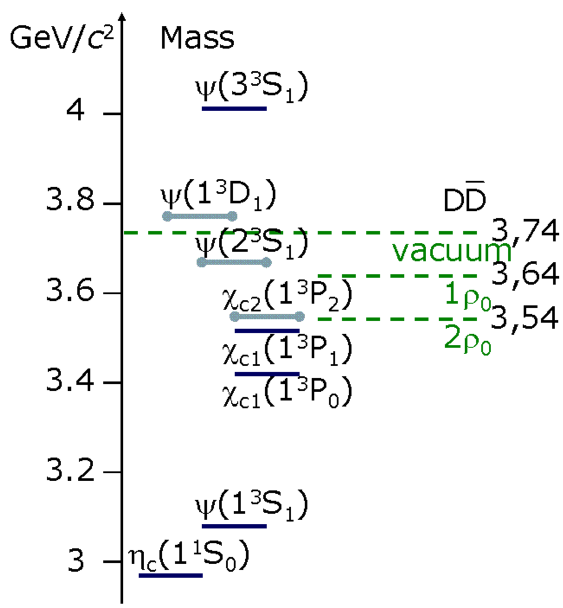

Figure 6:

Concerning a possible mass shift of the charmonium states, a theory model [13] predicts even a significant mass shift, as bigger as higher the mass of the state, e.g. –120 to –140 MeV for the $\psi(3770)$, which could be observed looking to the decay in dileptons, or for the $\chi_{c0,1,2} \rightarrow J/\psi\gamma$, respectively.

The measurement of the J/ψ dissociation cross section in nuclei will also be essential for the high energy heavy ion collisions, where the suppression of J/ψ production is interpreted as one of the signatures for the formation of a quark-gluon plasma. PANDA could perform a complete set of measurements of the J/ψ (and ψ' ...) yields in $\bar{\text{p}}$ annihilation on different nuclear targets.

Double Λ-Hypernuclei

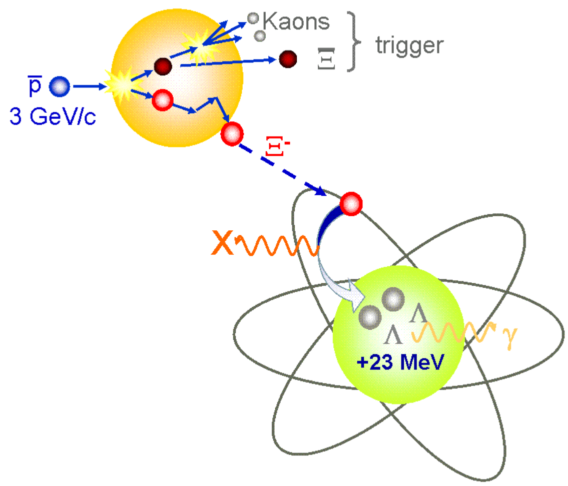

Figure 7:

Exploiting the annihilation of a 3 GeV/c $\bar{\text{p}}$ on a nucleus producing a $\Xi\bar{\Xi}$ hyperon pair, numerous $\Lambda\Lambda$ hypernuclei can be produced at PANDA. The slow Ξ^- (3 GeV/c is close to threshold) will be captured in a secondary target in the atomic orbit of a nucleus, where it cascades down to the nucleus, finally in a reaction with a proton, two Λ hyperons are produced in the nucleus. With a certain probability, they form a $\Lambda\Lambda$ hypernucleus. For the identification of the hypernucleus and the spectroscopy of its nuclear levels precision γ spectroscopy using Germanium detectors (EuroBall, VEGA type) will be applied. Figure 7 shows a sketch of the described reaction. The $\bar{\Xi}$ will serve as a tagger of the primary reaction, either by measuring the hyperon itself or the kaons produced in an annihilation inside the primary target nucleus.

This experiment will give the unique opportunity to study the $\Lambda\Lambda$ and ΛN interaction, as well as the investigation of the existence of a bound six quark (uuddss) state (H-particle, [14]).

Similar to the $\Xi\bar{\Xi}$ case, at a $\bar{\text{p}}$ momentum of 5.5 GeV/c $\Omega\bar{\Omega}$ can be produced. The long-lived Ω S=-3 hyperon (cτ = 2.46cm) is of particular interest since with $J = \frac{3}{2}$ it has a non-vanishing static quadrupole moment. If one captures a Ω^- in an atom of the secondary target, the study of the hyperfine splitting might be possible.

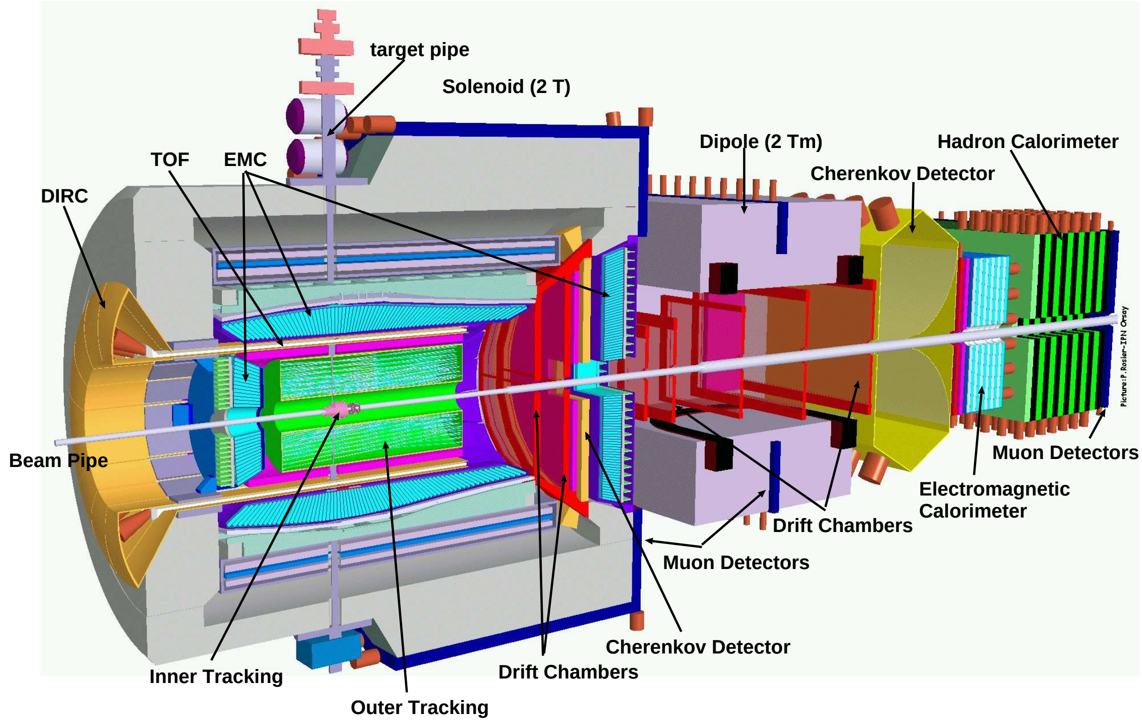

Figure 8:

The Detector Design

To investigate the described physics program, a multipurpose detector is needed. It should be able to deal with different targets, cover an angular range as complete as possible, identify charged ($e^{\pm}$, $\mu^{\pm}, \pi^{\pm}$, $K^{\pm}$,p, ...) and neutral particles (γ, π^0, η, ...) over a wide momentum range from 100 MeV/c to 8 GeV/c, be capable to stand $\approx 10^7$ interactions per second, resolve secondary decay vertices ($D^{\pm}$,D^0,K^0_s, Λ, Σ, ...) and be modular to a certain extend (hypernuclear physics setup, see below), furthermore have a sophisticated and efficient trigger system.

Figure 8 shows a cross-sectional view of the present design [5]. The beam is coming from the left. The setup is subdivided in a target spectrometer (using a superconducting solenoid of 2 T) and a forward spectrometer (comprising a dipole of 2 Tm bending power).

Target

Perpendicular to the beam pipe a target pipe will be placed, in which a stream of frozen hydrogen (or deuterium) pellets [15], a cluster jet [16] or a wire/fibre target can be implanted. The crossing of the two pipes is the interaction point.

Tracking Detectors

Directly at the cross of beam- and target pipe, close to the interaction point, a microvertex tracking detector, using silicon pixels and silicon strip techniques, will be adopted. Further out in radius, on outer tracking system, made from straw tubes (11 double layers of 6 and 8mm straw diameter, partly skewed) is planned. As an alternative option the use of a TPC with GEM readout as outer tracking device is under study. The tracking detectors will be completed by (multiwire) drift chambers for particles going to forward angles.

Particle Identification

For the particle identification, the target spectrometer will be equipped with an electromagnetic calorimeter (probably $PbWO_4$ crystals) with a barrel and forward and backward endcap sections. In front, a Čerenkov detector of the DIRC technique as well as a time-of-flight barrel are placed. In addition, for the forward angles, a RICH type detector will be installed. Going to even more forward angles, an electromagnetic followed by a hadron calorimeter will sit, and an additional Čerenkov detector, which might be replaced be a time-of-flight detector. Using the iron yoke of the magnets and the forward calorimeters as hadron absorbers, muon detectors will be implemented in target and forward spectrometer.

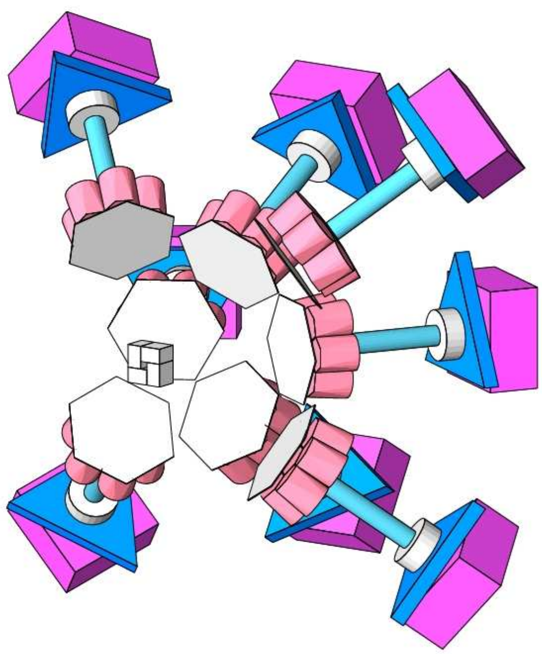

Figure 9:

Hypernuclear Physics Setup

For the hypernuclear physics experiment, the upstream part from the target pipe, i.e. the backward endcap of the electromagnetic calorimeter, will be replaced by a part of beam pipe holding the primary target (e.g. Ni foil), with the secondary target outside the vacuum - this target will be sandwiched by target material (e.g. Be, Li, C) and active tracking layers (Si strip). Finally, a number of Ge detectors for the γ spectroscopy will cover the backward acceptance. A possible setup is shown in Figure 9, where the beam comes from the right; the small cuboid is the secondery target, with eight Ge detectors looking to it.

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