

Experimental overview of the $\bar{\text{P}}\text{ANDA}$ experiment

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Abstract. The physics program of the $\bar{\text{P}}\text{ANDA}$ (anti-Proton ANihilation ar DArmstadt) experiment will address various questions related to the strong interactions by employing a multi-purpose detector system at the High Energy Storage Ring (HESR) for anti-protons of the upcoming Facility for Anti-proton and Ion Research (FAIR). The excellent antiproton beam resolution of $\Delta p/p \sim 10^{-5}$ and the high luminosity $\mathcal{L} = 2 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$ will allow the precise measurement of the charmonium and open charm spectroscopy, the search for exotic hadrons like multiquarks, glueballs and hybrids, the study of in-medium modifications of hadrons and the nucleon structure.

1. The FAIR facility

The recently approved FAIR facility, which will be built as a major upgrade of the existing GSI laboratory in Germany, will provide antiproton beams of the highest quality in terms of intensity and resolution. The FAIR facility consists of two synchrotron rings, called SIS100 and SIS300, housed in the same tunnel, which will provide proton and ion beams. The SIS100, a 100 T-m proton ring, will feed the radioactive ion and antiproton beam lines for experiments to be carried out in the HESR, the Collector and Cooler rings (CR) and the New Experimental Storage Ring (NESR). The SIS300 will deliver high energy ion beams for the study of ultra relativistic heavy ion collisions.

1.1. The High-Energy Storage Ring

The antiproton beam will be produced by a primary proton beam from the SIS100. The \bar{p} production rate will be $2 \times 10^7/\text{s}$. After 5×10^5 \bar{p} have been produced they will be transferred to the HESR, where the $\bar{\text{P}}\text{ANDA}$ experiment, in the \bar{p} momentum range from 1 GeV/c to 15 GeV/c can be performed. Two modes of operation are foreseen: the high intensity mode, where with a beam momentum spread $\Delta p/p = 10^{-4}$ a luminosity of $2 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$ will be available, and the high resolution mode, where the luminosity requirement will be relaxed to $10^{31} \text{ cm}^{-2} \text{ s}^{-1}$ to have a maximum momentum precision of 10^{-5} .

2. The $\bar{\text{P}}\text{ANDA}$ Physics Program

$\bar{\text{P}}\text{ANDA}$ will use the antiproton beam¹ at the HESR with momentum range between 1.5 GeV/c and 15 GeV/c, corresponding to total center-of-mass energies in the antiproton-proton system between 2.25 GeV and 5.5 GeV. The $\bar{\text{P}}\text{ANDA}$ experiment aims at exploring hadronic matter by means of the gluon rich environment of the $\bar{p}p$ annihilation which allows to access a wide range of

¹ The antiprotons are created by colliding high intensity protons with a copper target



final states. The 4π acceptance of the detector for both charged and neutral particles, together with the envisaged high quality of the antiproton beam, will create an ideal environment to collect high statistics data to address many open problems related with the strong interaction. PANDA will perform a complete program of hadron spectroscopy to test many unclear aspects of Quantum Chromo Dynamics (QCD) (Fig. 1). The aim is to investigate both the dynamics of the interaction, and the characteristics of new forms of matter such as exotic states in the charm energy range. Furthermore, particles properties, when produced inside the nuclear medium, and the structure of hadrons, will be investigated.

In this paper we will discuss the following aspects of the PANDA physics program [1]: the charmonium spectroscopy, the search for gluonic excitations (hybrids and glueballs), the study of hadrons in nuclear matter, the open charm spectroscopy and the hypernuclear physics.

2.1. Charmonium spectroscopy

Experimentally charmonium has been studied in e^+e^- and $\bar{p}p$ experiments. In e^+e^- annihilations direct charmonium formation is possible only for states with the quantum numbers of the photon $J^{PC} = 1^{--}$. Precise measurements of the masses and widths of these states can be obtained from the energy of the electron and positron beams, which are known with good accuracy. All other states can be reached by means of other production mechanisms. On the other hand, all $c\bar{c}$ states can be directly formed in $\bar{p}p$ annihilations, through the coherent annihilation of the three quarks in the proton with the three antiquarks in the antiproton. With this method the masses and widths of all charmonium states can be measured with excellent accuracy, determined by the very precise knowledge of the initial $\bar{p}p$ state and not limited by the resolution of the detector.

The spectrum of charmonium states consists of eight narrow states below the open charm threshold (3.73 GeV) and several tens of states above the threshold. All eight states below $D\bar{D}$ threshold are well established, but whereas the triplet states are measured with very good accuracy, the same cannot be said for the singlet states. For instance, the η_c was discovered almost thirty years ago but the mass and width measurements are far from satisfactory [2]. An additional topic is the study of the $\eta_c(2S)$, its properties need to be measured with good accuracy. Another open question is the spin-dependence of the $q\bar{q}$ confinement potential. With this aim, a precise measurement of the mass, width and decay channels of the singlet-P resonance, h_c , is of extreme importance.

The region above threshold is rich in interesting new physics. A lot of new states have recently been discovered at the B-factories, mainly in the hadronic decays of the meson: these new states (X, Y, Z) are associated with charmonium because they decay predominantly into charmonium states but their interpretation is far from obvious. For instance one of the most established among the XYZ states is the narrow X(3872) discovered by Belle [3]. For the width of this state only an upper limit has been established, and PANDA will be ideal to perform this measurement. An additional state is the Y(4260) discovered by BaBar [4], for which the interpretation is not so obvious.

At full luminosity PANDA will be able to collect several thousand $c\bar{c}$ states per day. By means of fine scans it will be possible to measure masses with accuracies of the order of 100 KeV and widths to 10% or better. The entire energy region below and above open charm threshold will be explored.

2.2. Gluonic excitations

An important item in the PANDA physics program is the search for gluonic excitations, i.e. hadrons in which the gluons can act as principal components. The gluonic hadrons fall into two categories: glueballs, states of pure glue, and hybrids, which consist of $q\bar{q}$ pair and excited glue. The additional degrees of freedom carried by gluons allow these hybrids and glueballs to have

J^{PC} exotic quantum numbers: in this case mixing effects with nearby $q\bar{q}$ states are excluded and this makes their experimental identification easier.

Antiproton-proton annihilations provide a very favorable environment in which look for gluonic hadrons. Two particles, first seen in πN scattering [5] with exotic quantum numbers $J^{PC} = 1^{-+}$, $\pi_1(1400)$ [6] and $\pi_1(1600)$ [7], are clearly seen in $\bar{p}p$ annihilation at rest. On the other hand a narrow state at 1500 MeV/c² discovered in $\bar{p}p$ annihilations by the Crystal Barrel experiment [8], is considered the best candidate for the glueball ground state ($J^{PC} = 0^{++}$), even though the mixing with nearby $q\bar{q}$ states makes this interpretation difficult. So far the experimental search for glueballs and hybrids has been mainly carried out in the mass region below 2.2 GeV/c². PANDA will extend the search to higher masses, and in particular to the charmonium mass region, where light quark states form a structure-less continuum and heavy quark states are far fewer in number. Therefore exotic hadrons in this mass region could be resolved and identified unambiguously.

2.3. Hadrons in nuclear matter

The study 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 its partial restoration in a hadronic environment. So far experiments have been focused on the light quark sector: evidence of mass changes for pions and kaons have been deduced by the study of deep bound pionic atoms [9] and of K meson production in proton-nucleus and heavy-ion collisions [10].

The high-intensity \bar{p} beam of up to 15 GeV/c will allow an extension of this program to the charm sector both for hadrons with hidden and open charm. The in-medium masses of these states are expected to be affected primarily by the gluon condensate. Recent theoretical calculations predict small mass shifts (5-10 MeV/c²) for the low-lying charmonium states [11] and more consistent effects for the χ_{cJ} (40 MeV/c²), ψ' (100 MeV/c²) and $\psi(3770)$ (140 MeV/c²) [12]. D mesons, on the other hand, offer the unique opportunity to study the in-medium dynamics of a system with a single light quark. Recent theoretical calculations agree in the prediction of a mass splitting for D mesons in nuclear matter but, unfortunately, they disagree in sign and size of the effect.

Another study which can be carried out in PANDA is the measurement of J/ψ and D meson production cross sections in \bar{p} annihilation on a series of nuclear targets. The comparison of the resonant J/ψ yield obtained from \bar{p} annihilation on protons and different nuclear targets allows to deduce the J/ψ -nucleus dissociation cross section, a fundamental parameter to understand J/ψ suppression in relativistic heavy ion collisions interpreted as a signal for quark-gluon plasma formation.

2.4. Open charm physics

The HESR running at full luminosity and at \bar{p} momenta larger than 6.4 GeV/c would produce a large number of D meson pairs. The high yield (100 charm pairs per second around the $\psi(4040)$) and the well defined production kinematics of D meson pairs, would allow to carry out a significant charmed meson spectroscopy program which would include, for example, the rich D and D_s meson spectra.

The B-factory experiments have discovered several new resonances in the D and D_s sectors, where two of them are extremely narrow: the $D_{sJ}^*(2317)$ [13] and the $D_{sJ}(2457)$ [14]. These new states appear at unexpected locations, since their masses are more than 140 MeV/c² lower than expected from potential models. This has given rise to speculations about their nature. It is important to verify these findings by means of new measurements. Threshold pair production can be employed for precision measurements of the mass and the width of the narrow excited D states.

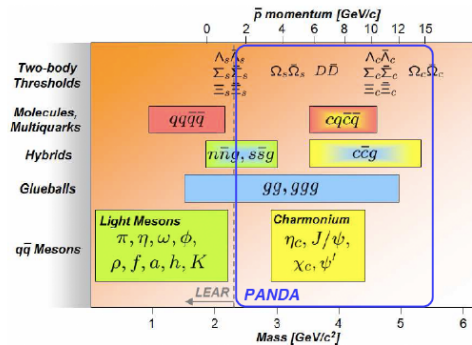


Figure 1. Mass range of hadrons accessible at $\bar{\text{P}}\text{ANDA}$.

2.5. Hypernuclei

The hypernuclei are systems where one (or more) nucleon is replaced by one (or more) hyperon(s). They are promising laboratories to study the hyperon-nucleon and hyperon-hyperon interactions. In 50 years of study very few double hypernuclei are presently known. With a dedicate setup of $\bar{\text{P}}\text{ANDA}$ and its antiproton beam, a copious production of double Λ -hypernuclei is expected to be observed, providing a precision investigation of the $\Lambda - \Lambda$ interaction. For this purpose, antiprotons at a moderate momentum of 3 GeV/c will interact with a primary target to produce large numbers of $\Xi\Xi$ pairs. The Ξ decay provides a unique signature for the production. The corresponding Ξ particle will be stopped and captured in a secondary target. In case the Ξ is absorbed inside the nucleus, it will yield a Λ pair with very small relative energy. A double hypernucleus can be formed as well and its decay could be observed with spectroscopic precision by using Germanium detectors.

3. The $\bar{\text{P}}\text{ANDA}$ Detector

In order to accomplish the physics program discussed above, the $\bar{\text{P}}\text{ANDA}$ detector must fulfill a number of requirements: it must provide full solid angle coverage, it must be able to handle high rates with good particle identification and momentum resolution for γ, e, μ, π, K and p . Additional requirements are vertex reconstruction capability, efficient lepton identification and excellent calorimetry, both in terms of resolution and of sensitivity to low energy showers. The schematic view of the detector is shown in Fig. 2. The antiprotons circulating in the HESR hit an internal hydrogen target (either pellet or cluster jet). The apparatus consists of a central detector, called Target Spectrometer (TS) and a Forward Spectrometer (FS). The TS, for the measurement of particles emitted at laboratory angles larger than 5° , will be located inside a solenoidal magnet which provides a field of 2 T. Its main components will be a micro vertex silicon detector, a central tracker (straw tube detector), an inner time-of-flight telescope, a cylindrical DIRC (Detector of Internally Reflected Light) and electromagnetic calorimeter, a set of muon counters and of multiwire drift chambers. The FS will detect particles emitted at polar angles below 10° in the horizontal and 5° in the vertical direction. It will consist of a 2 T·m dipole magnet, with tracking detectors, Cherenkov and time-of-flight detectors, electromagnetic and hadron calorimeters.

4. Conclusions

The availability of high-intensity, cooled antiproton beams at FAIR will make it possible to perform a very rich experimental program. The $\bar{\text{P}}\text{ANDA}$ experiment will perform high-precision hadron spectroscopy from $\sqrt{s} = 2.25$ GeV to $\sqrt{s} = 5.5$ GeV and produce a wealth of new results:

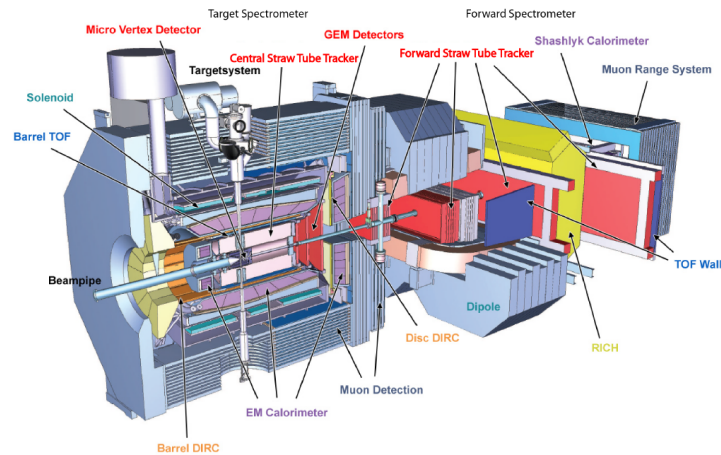


Figure 2. Schematic view of the $\bar{\text{P}}\text{ANDA}$ detector.

- precision measurement of the parameters of all charmonium states, both below and above open charm threshold, with the possible discovery of the missing states which will lead to a full understanding of the charmonium spectrum;
- the observation/discovery of glueballs and hybrids, particularly in the mass range between 3 and 5 GeV/c^2 , yielding new insights into the structure of the QCD vacuum;
- the measurement of mass shifts of charmonium and open charm mesons in nuclear matter, related to the partial restoration of QCD chiral symmetry in a dense nuclear medium;
- open charm spectroscopy (D and D_s spectra);
- the hypernuclear physics.

The $\bar{\text{P}}\text{ANDA}$ physics program includes other topics, which are not explained in this paper, for instance, the study of the structure of the nucleon using electromagnetic processes and electroweak physics (CP-violation).

All these new measurements will make it possible to achieve a very significant progress in our understanding of QCD and the strong interaction.

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