The \textit{PANDA} Experiment at FAIR

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\textbf{Abstract.}

The \textit{PANDA} experiment (Pbar ANnihilations at DArmstadt) is a next generation hadron physics detector under design for the Facility for Antiproton and Ion Research (FAIR) at Darmstadt, Germany. It will be using cooled antiproton beams with an energy between 1.5 GeV and 15 GeV interacting with various internal targets.

The experiment is focusing on hadron spectroscopy, in particular the search for exotic states in the charmonium region, on the interaction of charm hadrons with the nuclear medium and on double-hypernuclei.

With physics requiring precise partial wave analysis the experiment has almost 4\pi acceptance, a solenoid magnet for high \(p_T\) tracks and a dipole magnet for the forward part of reaction products. A silicon vertex detector surrounds the interaction point. In both spectrometer parts tracking, charged particle identification, electromagnetic calorimetry and muon identification are available.

The experiment is being designed to fully exploit the extraordinary physics potential arising from the availability of high-intensity, cooled antiproton beams.

Significant progress beyond the present understanding of the field is expected thanks to improvements in statistics and precision of the data.

\textbf{Keywords:} New Facilities, Antiproton beams, Precision Experiments


\textbf{THE FAIR PROJECT}

The Gesellschaft für Schwerionenforschung (GSI) [1] of Darmstadt (Germany) is undergoing a major upgrade of the existing laboratory [2]. This upgrade foresees ion beams of higher intensity and better quality, and, first for GSI, an antiproton beam.

The heart of this new facility is a double-ring tunnel with a circumference of 1100 meters that will house 2 sincrotrons, SIS100 and SIS300. The goal of the SIS100 is to achieve intense pulsed (5 \(\cdot\) 10\(^{11}\) ions per pulse) \(U\)\(^{28+}\) beams at 1 AGeV, and an intense (4 \(\cdot\) 10\(^{13}\)) pulsed proton beam at 29 GeV. For the supply of the high-intensity proton beam, which is required for antiprotons production, a separate proton linac as injector of the SIS18 synchrotron will be constructed.

The SIS300 will provide high-energy ion beams of maximum energies around 45 AGeV for \(Ne\)\(^{10+}\) beams, and close to 35 AGeV for fully stripped \(U\)\(^{92+}\) beams. The maximum intensities will be close to 1 \(\cdot\) 10\(^{9}\) ions/s. Adjacent to the double-synchrotron system, there will be a complex of storage-cooler rings and experimental stations, including a Superconducting Fragment Separator (Super-FRS), and an antiproton production target, that will supply rare isotope beams and antiproton beams with unprecedented intensity and quality.

At FAIR the antiprotons will be available for the experimental activity at the High Energy Storage Ring (HESR), a slow ramping synchrotron and storage ring equipped with stochastic and electron cooling to provide excellent beam energy definition. Here the beam energy could be varied from 3 GeV up to a maximum of 14.5 GeV.

The HESR will have two different operation modes: the high intensity mode, where with a beam momentum spread \(\delta p/p = 10^{-4}\) a luminosity of 2 \(\cdot\) 10\(^{32}\) cm\(^{-2}\)s\(^{-1}\) will be available, and the high resolution mode, where the luminosity requirement will be released to 10\(^{31}\) cm\(^{-2}\)s\(^{-1}\) to have a maximum momentum precision of 10\(^{-5}\). This will allow to measure masses and widths of hadronic states with an accuracy down to 50-100 keV never obtained up to now; as a comparison, existing and/or planned \(e^+e^−\) colliders can get values from 10 to 100 times worsed.
THE PANDA SCIENTIFIC PROGRAM

One of the most challenging and fascinating goals of modern physics is the achievement of a fully quantitative understanding of the strong interaction, which is the subject of hadron physics. Significant progress has been achieved over the past few years thanks to considerable advances in experiment and theory. New experimental results have stimulated a very intense theoretical activity and a refinement of the theoretical tools.

Still there are many fundamental questions which remain basically unanswered. Phenomena such as the confinement of quarks, the existence of glueballs and hybrids, the origin of the masses of hadrons in the context of the breaking of chiral symmetry are long-standing puzzles and represent the intellectual challenge in our attempt to understand the nature of the strong interaction and of hadronic matter.

Experimentally, studies of hadron structure can be performed with different probes such as electrons, kaons, protons or antiprotons. In $\bar{p}p$ annihilation particles with gluonic degrees of freedom, as well as particle-antiparticle pairs, are copiously produced, allowing spectroscopic studies with very high statistics and precision. Therefore, antiprotons are an excellent tool to address the open problems.

The PANDA experiment aims at exploring hadronic matter by means of the gluon rich environment of antiproton-proton annihilation which allows to access a wide range of final states.

The $4\pi$ acceptance of the detector either for 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). 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, and nuclei with an explicit strange quark content. Furthermore, particle properties, when produced inside the nuclear medium, and the structure of hadrons, will be investigated.

A complete description of all the aspects of the PANDA scientific program can be found in [3]. Four major physical research topics will be addressed:

- High precision spectroscopy of resonances in the energy region of charmonium and above. The exact knowledge about masses, widths, and branching ratios provides information about the mechanisms of quark confinement.
- In-medium effects of open and hidden charm and their relationship to the chiral symmetry breaking addressing especially the origin of hadron mass.
- So-called glueballs, predicted by QCD, need a firm experimental establishment in our picture of strong interactions. Also hybrid meson states, so-called excited glue, in the mass range between 3 and 5 GeV/c$^2$ are predicted to be rather narrow without mixing into neighboring resonances.
- Hypernuclei, when abundantly produced, and examined with the next generation of $\gamma$-detectors, will revive the physics with single and double hypernuclei. This will improve our modest knowledge on their structure and give information on the interaction of hyperons with nucleons as well as hyperon-hyperon interaction.

GSI has a distinguished history of having made important contributions to the physics of strong interaction, in particular nuclear physics. The proposed PANDA experiments play a significant role in strong interaction physics, providing a link between nuclear and hadron physics.

THE PANDA SPECTROMETER

To achieve almost $4\pi$ acceptance and good momentum resolution over a large range, a solenoid magnet for high $pr$ tracks (target spectrometer) and a dipole magnet for the forward part of reaction products (forward spectrometer) are foreseen (see Fig. 1)

A silicon vertex detector surrounds the interaction point. In both spectrometer parts tracking, charged particle identification, electromagnetic calorimetry and muon identification are available. States with many photons can occur, leading to a low photon threshold of few MeV and a dynamic range up to 10 GeV as requirements for the electromagnetic calorimeters. Several detectors for charged particle identification cover a large momentum range from several hundred MeV to several GeV for electrons, pions, kaons, protons and muons.

For the reconstruction of invariant masses a good momentum resolution in the order of $\delta p/p \approx 1\%$ is desirable. Low cross-section processes and precision measurements lead to a high rate operation at 20 million interactions per second.
The PANDA detector consists of a central and a forward magnetic spectrometer. The figure shows the subdetectors within the solenoid and subdetectors inside and behind the dipole magnet of the forward spectrometer.

To operate the experiment at high rate and with different parallel physical topologies a self-triggering readout scheme was adopted. The frontend electronics continuously digitizes the detector data and autonomously finds valid hits. Physical signatures like energy clusters, tracklets or ringlets are extracted on the fly. Event selection is only performed in software online. This allows full flexibility in applying selection algorithms based on any physics signatures detectable by the spectrometer. In addition physics topics with identical target and beam settings can be treated in parallel.

The target spectrometer

The target spectrometer is working in a solenoidal magnetic fields up to 2 Tesla. As target, both, a hydrogen cluster jet target and a hydrogen pellet target, with an areal density up to $10^{16}$ atoms/cm$^2$, are foreseen, to reach the required luminosity and to allow the determination of the primary vertex. Both of them can also be operated with heavier elements. The target station is surrounded by tracking detectors and particle identification detectors for charged particles. In addition an electromagnetic calorimeter is capable of gamma detection and electron/pion separation.

A microvertex detector (MVD) with 4 barrels around and 8 disks pointing towards the interaction point serves as tracker also for secondary vertices as close as 50 $\mu$m from the interaction point to resolve D-mesons. The silicon vertex detector consists of two inner layers of hybrid pixel detectors and two outer layers with silicon strip detectors. In forward direction there are 6 disks with both pixel and strip modules. The pixel modules are based on a custom-made self-triggering readout ASIC realized in 0.13 $\mu$m CMOS with 100 $\cdot$ 100$\mu$m$^2$ pixel size and cover 0.15 m$^2$ with 13 million channels. The strip part is based on double sided silicon strips read by a self-triggering 128-channel ASIC with zero suppression and analog readout and covers 0.5 m$^2$ with 70 000 channels.

Together with the microvertex detector the information of a central racker yields information about the momentum of the charged particles. For the tracking in the solenoid field low-mass straw tubes arranged in straight and skewed configuration are foreseen. The straws have a diameter of 1 cm and a length of 150 cm and are operated with $Ar/CO_2$ at 1 bar overpressure giving them rigidity without heavy support frames. As alternative an ungated Time Projection Chamber based on GEM foils as readout stage is being developed. The GEM foils suppress the ion backflow into the drift volume minimizing the space charge build-up. As detector gas $Ne/CO_2$ is used. The readout plane consists of
100,000 pads of 2·2 mm². With 500 hits per track and more than 50 μs drift time, 500 events are overlapping leading to a very high data rate which has to be digested online.

In the forward endcap large area GEM detectors with high rate capability and low material budget due to ultra-thin coating are employed. They are followed by straw chambers in the forward spectrometer.

Particle IDentification

Particle identification is required over a large momentum range from 200 MeV/c up to almost 10 GeV/c. Different physical processes are employed.

The main part of charged particles is identified by various Cherenkov detectors. Due to the compactness of the \( \bar{P} \)ANDA detector, only limited space is available and makes the DIRC principle favorable, as it was working in the BaBar detector at SLAC [4]. DIRC stands for Detecting Internally Reflecting Cherenkov photons. The barrel consists out of 200 artificial fused silica slabs which reflect, downstream by a mirror, photons back towards the photon detector. Here, the photons are focussed by a lens system on a flat focal plane [5]. This plane will be read out by Micro-channel- PMTs [6] which can work within the field of the solenoid of B=1 Tesla.

Additional timing information, when in the sub-nanosecond range, can help to correct the Cherenkov images when distorted by dispersion. The over-determination of the Cherenkov image by the position and timing information of the photons allows to measure the wavelengths of the photons. We consider two options of a timing barrel either based on RPC counters or on scintillation counters.

A prototype of a segment of this counter was tested in a 2 GeV test beam with protons [11]. The setup is a radiator coupled to an expansion box with photon detection on its back. The readout electronics operate in close distance to the photon detector and send the data by network to the backend computers.

The proton beam hit the quartz bar with different adjustable angles. A scintillator paddle is used as coincident trigger. Four 8·8 pixel MCP-PMTs from Burle are attached at the rear side of a expansion box filled with Marcol-81 oil (Fig. 2 - Left Panel). The synthetical fused quartz radiators are coupled to this expansion box with a focussing lens. The oil, with a refractive index similar to that of the radiator, minimizes image distortions of the Cherenkov rings. The NINO-discriminators of of each amplified (x10) MCP- PMT channel are set to thresholds of 44 mV. Finally, for the readout 2 HADES-TRB (TRBv2) are used [12].

The measured pixel pattern of the four MCP-PMTs is shown on the right panel of Fig. 2. The left top detector covers only partially the acceptance of the expansion volume indicated by the gray shaded area. The left bottom detector suffers from broken electronic channels. The expected ring structures as indicated by the dotted lines are clearly seen. They also move in the right way, when the inclination angle of the beam with the radiator is changed.

The Cherenkov counter in forward direction will be a disk made from artificial fused silica. Readout either by a two-dimensional position sensitive detector [7, 8], or by a one dimensional position sensitive detector along the rim records the Time-of-Propagation (TOP) of the photons [9]. In the first case the light is coupled out from the disk by a focussing light guide towards the photon detector. The one dimensional position of the photon on this detector together with the detector position along the disk rim gives the two dimensional spatial Cherenkov image. In the latter case (TOP) the Cherenkov angle resolution can be improved by using dichroic filters in front of the photon detectors. Then photons of two color ranges are either recorded or reflected towards the next photon detector increasing the time of flight.

Time of flight can be partly exploited in \( \bar{P} \)ANDA. However, only relative timing of charged particles can be measured since to minimize material there is no start detector. The energy loss within the trackers will be employed as well for particle identification below 1 GeV/c since the charge deposit is obtained by analog readout or time-over-threshold measurement. Here the TPC option would provide best performance. The detection system is complemented by muon detectors based on drift tubes located inside the segmented magnet yoke, between the magnets and at the end of the setup.

In the target spectrometer high precision electromagnetic calorimetry is required over a large energy range from a few MeV up to several GeV. Lead-tungstate is chosen for the calorimeters in the target spectrometer due to its good resolution, fast response and high density allowing a compact setup. This calorimeter is described in a Technical Design Report [10].

To achieve the very low threshold the light yield has to be increased. Therefore improved lead-tungstate crystals with a twice higher light output compared to CMS are employed. They are operated at −25°C which triples the output another time. In addition large area APDs are used for readout giving high quantum efficiency and a four times larger...
FIGURE 2. Left Panel: Prototype setup for measurements in proton beams. The radiator coming from the bottom right is hit by a relativistic proton beam and the Cherenkov photons propagate towards the photon detectors seen as square objects at the back of the expansion volume. Right Panel: The observed Cherenkov ring pattern with the expected position (dotted lines). The shaded area indicates the acceptance of the expansion volume.

active area compared to CMS. The largest sub-detector is the barrel calorimeter with 11000 crystals of 200 · 20 · 20 mm³ size. The length of the crystals is about 20 X₀ and yields an energy resolution of \( \sigma/E = 1.5\%/\sqrt{E} \).

The operation at low temperatures imposes a technological challenge on the mechanical design, the cooling concept and thermal insulation under the constraints of a minimum material budget of dead material. Detailed simulations and prototyping have confirmed the concept and high accuracy has been achieved in temperature stabilization taking into account also realistic scenarios of the power consumption of the front-end electronics.

Concepts for the photon sensors and the readout electronics have been tested. As the most sensitive element, a prototype of a custom designed ASIC implementing preamplification and shaping stages has been successfully brought into operation and will provide a large dynamic range of 12,000 with a typical noise level corresponding to \( \approx 1 \) MeV. Based on the ongoing developments of PWO-II crystals and LAAPDs, respectively, a detailed program has been elaborated for quality assurance of the crystals and screening of the photo sensors. Prototypes of the individual crystal containers, based on carbon fiber alveoles, have been fabricated and tested and are already implemented in the PROTO60 device. The experimental data together with the elaborate design concepts and simulations show that the ambitious physics program of \( \bar{P}ANDA \) can be fully explored based on the measurement of electromagnetic probes, such as photons, electrons/positrons or the reconstruction of the invariant mass of neutral mesons.

In the backward direction 800 crystals provide hermeticity at worse resolution due to the presence of readout and supply lines of other detectors. The 4000 crystals in the forward direction face much higher particle rates across the acceptance of the calorimeter in the forward endcap. A readout with vacuum triodes is considered to cover the higher radiation load.

The subsystems are modular and removable to allow the insertion of different detector types. The hypernuclear physics eg. requires the insertion of a primary target and a secondary target/tracker detector with surrounding high resolution gamma detectors, which is possible due to the flexible modular detector concept [13].

The Forward spectrometer

In a fixed target experiment particles are copiously emitted in forward direction and the need for measuring all the particles for eg. partial wave analysis makes a forward spectrometer indispensable.

The heart of the forward spectrometer is a dipole magnet with a large opening angle and a bending power of 2.
This will provide the required momentum resolution for forward tracks with momenta up to 8 GeV/c. Tracking is provided by minidrift chambers. In front of the magnet, they have the same octonal shape as in the end-cap of the target spectrometer. Behind the magnet, a rectangular shape is more suitable for the spread of the tracks. The use of straw tube trackers inside the dipole field is considered for better momentum resolution. The option of a third Cherenkov counter, based on gas or aerogel is still under investigation. In addition, a time-of-flight detector is considered for charged particle identification. An electromagnetic calorimeter based on lead/scintillator sampling and WLS fibre readout (Shashlyk type) is foreseen in the forward spectrometer. It will reach a resolution of $4%/\sqrt{E}$.

### PHYSICS PERFORMANCES

The performances of the detector and the sensitivity to the various physics channels have been estimated by means of detailed Monte Carlo simulations [14]. The aim of these benchmark studies was to demonstrate the feasibility of the planned physics program and moreover to show the expected physics performance for the upcoming measurements with the PANDA detector. This requires accurate simulation studies of the physics channels of interest and of the relevant background by taking into account the complete $\bar{p}p$ planned physics programme.

A huge number of background events were needed because the total antiproton-proton cross section in this energy regime is between 50 - 100 mb and, compared to that, the cross sections of most physics channels are expected to be very low and are typically in the order of pb or nb. In order to meet these requirements an offline software has been devised following an object oriented approach and making use of several well-tested software tools and packages from other HEP experiments. These packages have been adapted to the PANDA needs.

The generation and processing of the data is subdivided into a couple of well defined stages: the event generation, the particle tracking utilising the GEANT4 transport code, the digitisation, which models the signals and their processing in the front-end electronics of the detectors, the reconstruction, which finally creates lists of particle candidates, and at the last stage, the physics analysis. For this final step the software provides besides low-level analysis tools also high-level analysis tools, which allow to reconstruct decay trees, perform geometrical and kinematic fits, and to refine the event selection in a very easy and user friendly manner.

Thanks to the software tools developed the performance of the detector and the sensitivity to the various physics channels have been estimated reliably in terms of geometrical acceptance, resolution and signal/background ratios. For the benchmark channels chosen the simulations show that the final states of interest can be detected with good efficiency and that the background contamination is at an acceptable level. This demonstrates the feasibility of the planned physics programme.

Two illustrative results of the simulations are shown in Fig. 3. In particular in the left panel the reconstructed $h_c$ (from the decay $\bar{p}p \rightarrow h_c \rightarrow J/\Psi + \gamma$) is shown. Indeed one of the main problems in the experimental study of charmonium spectroscopy in $\bar{p}p$ annihilation is the high hadronic background. It is therefore necessary to select those decays of charmonium which are less affected by background.

The study of resonances is an important part of the PANDA physics programme. Masses, widths and decay fractions are measured by scanning the beam energy across the resonance under study. In antiproton-proton annihilations, there are two main advantages over inclusive production:

- resonances can be formed directly;
- the detector is used as an event counter (y axis of the excitation curve), while the energy determination (x axis) relies entirely on the precisely-calibrated and cooled antiproton beam.

In order to assess the ability to measure narrow widths a study of the sensitivity of PANDA to the determination of various resonances was undertaken. For the $h_c$ width study, for example, we performed Monte Carlo simulations of energy scans around the resonance. Events were generated at 10 different energies around the $h_c$ mass, each point corresponding to 5 days of running the experiment in high resolution mode.

Other challenging benchmark channels are those characterized by very high photon multiplicities. In the right panel of Fig. 3 an example of the invariant mass simulated for $\bar{p}p$ in open charm with a recoiling $\eta$ meson is shown.

In particular for the production of $\eta_{c1}$ in $\bar{p}p \rightarrow \eta_{c1}\eta$ it is assumed that the cross section is in the same order of magnitude as for the process $\bar{p}p \rightarrow \Psi(2S)\eta$ including conventional charmonium. The final state with 7 photons and an $e^+e^-$ lepton pair originating from $J/\Psi$ decays has a distinctive signature and separation from light hadron background should be feasible. A source of background are events with hidden charm, in particular events including a $J/\Psi$ meson. Photon candidates are selected from the clusters found in the EMC. Photon and $J/\Psi$ candidates are accepted if

\[ \text{Tm.} \]
their invariant mass is within defined physical intervals. From these events candidates are created, where the same photon candidate does not occur more than once in the final state. The corresponding tracks and photon candidates of the final state are kinematically fitted by constraining their momentum and energy sum to the initial $\bar{p}p$ system and the invariant lepton candidates mass to the $J/\Psi$ mass. For the final event selection the same kinematic fit is repeated with additionally constraining the invariant $\chi_{c1}, \pi_0$ and $\eta$ mass to the corresponding nominal mass values. Candidates having a confidence level less than 0.1% are rejected. To ensure an unambiguous reconstruction of the total event, events with a candidate multiplicity higher than one are rejected.

The invariant $\chi_{c1}\pi_0\pi_0$ mass obtained after application of all selection criteria is shown in the right panel of Fig. 4. The $\eta_{c1}$ signal has a FWHM of 30 MeV/c$^2$. The reconstruction efficiency is determined from the number of $\eta_{c1}$ signal entries in the mass range 4.24 ± 4.33 GeV/c$^2$ and is found to be 6.83%.

An additional example of the performance of the detector and the sensitivity to the physics program of the $\bar{P}$ANDA experiment, the results of spectroscopic studies on $\Lambda\Lambda$ hypernuclei is shown in Fig 5. Double hypernuclei will be produced at $\bar{P}$ANDA via a two-steps mechanism [14]. Therefore, spectroscopic information on double hypernuclei will only be obtained via their decay products. Except for the case of very light hypernuclei also neutral particles are emitted unfortunately. Therefore, a unique identification of the double hypernuclei can only be reached via the emitted $\gamma$-rays from excited, particle stable states. In the simulation [13] the excited double hypernuclei decay electromagnetically to the ground state, and a sequential pionic decay takes place. Since the momenta of the two pions emitted sequentially are strongly correlated their coincident measurement provides an effective method to tag the production of a double hypernuclei. Fig. 4 (left panel) shows the momentum correlation of all negative pion candidates emitted from the sequential mesonic decay. The various bumps correspond to the different double hypernuclei in a secondary $^{12}$C target. Those which are mostly produced are marked with empty boxes. The region enclosed by each box will be used to gate the energy spectra of the corresponding double hypernuclei as it is shown in the right panel of Fig. 4. The arrows mark the expected $\gamma$-transitions energies from single and double hypernuclei. With additional factors, the spectra shown in Fig. 4 correspond to a running time at $\bar{P}$ANDA of about two weeks. The final rate may be significantly improved by up to a factor 10 by gating on double non mesonic weak decays or on mixed weak decays.

**SUMMARY**

The availability of high-intensity, cooled antiproton beams at FAIR will make it possible to perform a very rich experimental program.

The $\bar{P}$ANDA experiment will perform high-precision hadron spectroscopy from $\sqrt{s} = 2.25$ GeV to $\sqrt{s} = 5.5$
FIGURE 4. Left Panel: Momentum correlation of all negative pion candidates resulting from the decay of double hypernuclei in a secondary $^{12}$C target. Right Panel: $\gamma$–spectra detected in the HPGeArray by cutting on the two pion momenta. The expected $\gamma$–transitions energies from single and double hypernuclei are marked by the arrows.

GeV and produce a wealth of new results in hadron spectroscopy and nucleon structure. $\bar{P}$ANDA will become a versatile QCD experiment with large acceptance owing to its double spectrometer providing tracking and vertexing capabilities, particle identification and calorimetry. The flexible readout concept makes of $\bar{P}$ANDA a programmable physics machine ready for any measurement in reach by the apparatus itself. Novel techniques in detector and readout design are employed.

The performances of the detector and the sensitivity to the various physics channels have been estimated by means of detailed Monte Carlo simulations, which show that the final states of interest can be detected with good efficiency and low background. 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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