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The $\overline{\mathrm{P}}$ANDA Experiment at FAIR

The world facility for QCD studies

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Abstract The $\overline{\mathrm{P}}$ANDA experiment is a core project of the future Facility for Antiproton and Ion Research (FAIR) at GSI in Darmstadt. It will investigate antiproton-proton annihilations on nucleons and nuclei with the aim to explore fundamental questions in the non-perturbative regime of QCD as the origin of the hadron mass. The multi-purpose detector is currently under construction. The intense and high quality anti-proton beam will span the momentum range between 1.5 and 15 GeV/c. Properties of hadrons, leptons, and photons in the final states will be determined with very high precision. A rich physics program including the study of resonances in the charmonium and open charm region, electromagnetic form factors, and hypernuclear physics is planned. The worldwide collaboration gathers today more than 450 physicists from 60 institutions in 19 countries. An overview of the $\overline{\mathrm{P}}$ANDA experiment is given, focussing on aspects of the physics program that will be investigated as soon as the facility becomes operational.

Keywords Antiproton · Hadron structure · New facilities

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1 Introduction

The $\overline{\mathrm{P}}$ANDA experiment [1] is one of the four pillars of the future Facility for Antiproton and Ion Research (FAIR) at Darmstadt [2]. This complex accelerator is under construction on the site of the GSI laboratory and can be considered as an extension of the present facilities. However, the scale of

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the new project is much larger. High intensity proton beams will be accelerated and either used directly for an experiment or sent to a production target for antiproton beams. Four experiments, Atomic, Plasma Physics and Applications (APPA), Compressed Baryonic Matter (CBM), NUclear STructure, Astrophysics and Reactions (NUSTAR) and antiProton ANnihilation at DArmstadt ($\overline{\mathrm{P}}$ANDA) will investigate the main research topics in the related fields, where all physics community will be represented. About 3000 scientists from more than 50 countries are involved in the preparation of the physics program and in the construction of the the accelerator and the experiments. FAIR is built as a consortium of several countries, who participate as partners or as associate members.

After some delay following the first proposal, the groundbreaking ceremony for the FAIR accelerator facility took place on July 4th, 2017. Since this day, intensive work on the civil construction of FAIR is going on very efficiently. It can be followed on-line on the web site of FAIR by webcam [3] and it is recorded with animations and videos publicly available on the website. A large pedagogical effort in communication towards general public and students is done [4]. In parallel, the construction of the detectors is carried on, not only at GSI, but especially in the participating laboratories. This contribution gives an overview of the $\overline{\mathrm{P}}$ANDA experiment, highlighting those aspects that make the unicity of this experiment. Physics topics that can be investigated in the first stage of the experiment are illustrated.

2 The $\overline{\mathrm{P}}$ANDA experiment

The antiproton beam will be formed from a high intensity proton beam, accelerated by a 70 MeV linear accelerator (LINAC) and injected into the synchrotron ring SIS18 (in future into SIS100) impinging on a thick Ni/Cu production target. The antiprotons will be cooled in a collector ring (CR) and then injected into the High Energy Storage Ring (HESR). The $\overline{\mathrm{P}}$ANDA experiment can be considered as a fixed target experiment as well as an internal target experiment: antiprotons not interacting with the target (cluster jet or frozen pellet hydrogen target) recirculate in the HESR. The available range of momentum (center of mass energy) will be from 1.5 GeV/c to 15 GeV/c (from 2 to 5.5 GeV). The expected luminosity is $\mathcal{L} \sim 10^{31}\mathrm{cm}^{-2}$ s^{-1} in the start version. The high momentum resolution from 10^{-4} up to $5 \cdot 10^{-5}$ in the high resolution mode, together with the high performance of the detector will allow to perform a unique physics program. Note that the intensity of the antiproton beam ($2 \cdot 10^7$ $\bar{p}/s$) as well as the momentum resolution are one order of magnitude higher than previously reached at LEAR and FERMILAB.

To collect the information on specific hadronic as well as electromagnetic reaction channels from the antiproton-proton collisions, the $\overline{\mathrm{P}}$ANDA detector will provide precise trajectory reconstruction, energy and momentum determination and a very efficient identification of charged particles and photons. The huge hadronic background can be sufficiently suppressed to identify final-state

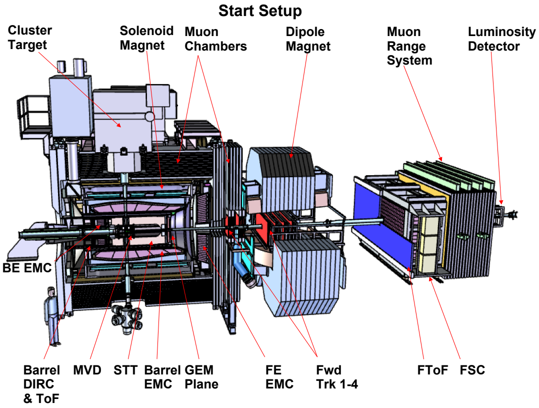

Fig. 1 Sketch of the start version of the $\overline{\text{P}}$ANDA set-up.

leptons. A sketch of the detector is shown in Fig. 1. A target spectrometer and a forward spectrometer insure a $\sim 4\pi$ acceptance. The interaction point will be determined with high precision (100 μm along the beam direction) using a MicroVertex Detector (MVD) surrounding the target region. Together with Gas Electron Multiplier (GEM) planes and Straw Tube Tracker (STT), in a 2-T solenoid magnet, a momentum resolution of $\sim 1\%$ will be achieved for charged particles. A DIRC barrel (Detection of Internally Reflected Cherenkov Light), a Time of Flight (ToF), and the energy loss measurement insure the detection of pions, kaons and protons. An Electromagnetic Calorimeter (EMC) of cooled Lead Tungsten crystals provides the detection of photons in a wide energy range, from 3 MeV to 10 GeV, with good resolution. Muon counters, one surrounding the magnet and one downstream allow to detect the muons. A Forward Tracking System (FTS), with straw planes in a dipole magnet, an aerogel RICH (Ring Imaging Cherenkov) counter, a time of flight and a Forward EMC constitute the forward spectrometer that ensures the detection of particles that scatter at small angle. Technical Design Reports (TDRs) have been published, followed by the construction and tests of prototypes of subdetectors [5].

In order to select events for offline analysis, PANDA will use a software-based triggerless online reconstruction. This is a real challenge in terms of data taking as well as storage. The large hadronic cross sections result in huge interaction rates, among which one has to select specific channels, which cross sections is of the order of few nb. The capability of selecting a final state depends on the signal-to-background ratio. The interesting channels are simulated with the help of a Monte Carlo simulation and analysis program, PANDARoot, that has been built and evolutes constantly to integrate the performances of the detector.

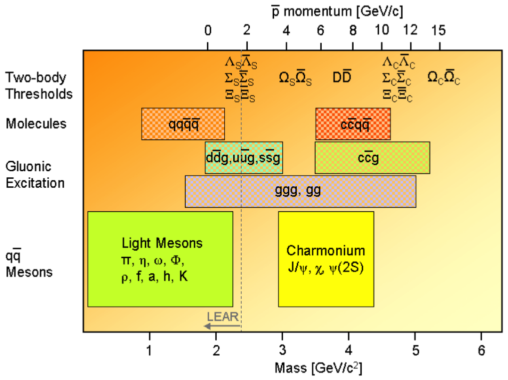

Fig. 2 Illustration of some of the physical objects accessible at $\overline{\mathrm{P}}$ANDA, as a function of their mass and of the $\bar{p}$ momentum.

3 The $\overline{\mathrm{P}}$ANDA Physics Program

The $\overline{\mathrm{P}}$ANDA physics program has the aim to improve our understandings of hadrons [1], of their constituents and of the dynamics driving their complex structure. Hadrons are the particles submitted to the strong interaction. In this respect antiprotons seem to be the favored probes, as their annihilation with matter produces a gluon rich environment. Gluons are spin-one massless bosons that play the role of mediators of the strong interaction. Their interaction is is possibly responsible for the dynamical generation of the mass of hadrons and it could explain the fact that the mass of the nucleon is ~100 times larger than the mass of its constituents, the quarks. Static properties as the proton radius are still object of controversy. The mechanism of quark confinement and the intrinsic structure of the nucleons are not fully understood. Particles as glueballs and hybrids may be formed and observed as resonances. The assignment of the quantum numbers and their decay properties constitute a large part of the $\overline{\mathrm{P}}$ANDA experimental program. Its discovery potential in the in the energy range of the recently observed XYZ states is due to specific features: - These states will be produced with high statistics; - All quantum numbers allowed by the quark model can be directly formed in $\bar{p}p$ reactions, whereas only $J^{PC} = 1^{--}$ states are directly formed in e^+e^- collisions, the XYZ states being formed in the decay of higher lying state; - Moreover, in the high momentum resolution mode of HESR, a precise energy scan will be possible. The observed width of the resonance will appear as a convolution of its intrinsic width and of the beam momentum resolution ($\Delta p/p \leq 4 \cdot 10^{-5}$), that is two order of magnitude better than the detector resolution. Therefore the mass and width, as well as the line shape of a resonance can be measured with high precision. This is a fine test of the models proposed for their structure, and of the underlying dynamics of their formation. In particular, the appearance of a resonance in production mode and its non-observation in direct formation mode is a clear signature of its exotic nature.

$\overline{\mathrm{P}}$ANDA will also copiously produce strange particles, where a strange quark replaces a light quark (up or down), opening the way to the observation of double strange hypernuclei. The spectroscopy of these nuclei, as well as a better knowledge of the ΛN and $\Lambda\Lambda$ interaction potential will help to understand the dynamics of QCD. Counting rates for the annihilation into hyperon-antihyperon pair have been estimated, showing that the study of these reactions will be meaningful also with the intensity that will be available at 'phase-1'.

The physics objects that will be studied at $\overline{\rm P}$ANDA are illustrated in Fig. 3 in terms of their mass. The beam momentum range is above the one investigated at LEAR. Heavier $\bar{q}q$ mesons will be formed, in particular the charmonium states, gluonic excitations, and quark molecular states. The $\bar{p}$ momentum will be well above the production threshold for open-charm pairs such as $\Lambda_c\bar{\Lambda}_c$, $\Sigma_c\bar{\Sigma}_c$, $\Xi_c\bar{\Xi}_c$ and sufficient to reach the $\Omega_c\bar{\Omega}_c$ threshold.

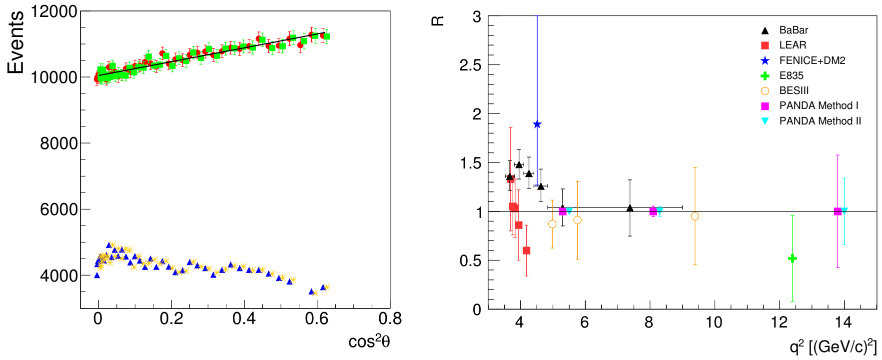

Fig. 3 Simulation and data on the electromagnetic form factor ratio in the time-like region. (left) Simulated events as a function of $\cos^2\theta$ for $q^2 = 5.4$ (GeV/c)^2, after efficiency correction: forward (backward) events as red circles (green squares); before efficiency correction: forward (backward) events as blue triangles (orange stars). (right) Existing data and expected statistical precision on the proton form factor ratio R = 1 at $\overline{\rm P}$ANDA (magenta circles and orange down triangles) as a function of q^2. The Figures are from Ref. [8].

In addition to the strong interaction studies, leptonic channels produced in $\bar{p}p$ annihilation allow to test the electromagnetic structure of the proton, through the measurement of the angular distribution for the reaction $\bar{p}p \to \ell^+\ell^-$, $\ell = e$ or μ and the determination of the electric and magnetic form factors in the time-like region. The hadron electromagnetic current for the $\bar{p}p$ annihilation in two leptons, assuming the exchange of a virtual photon of mass q^2, is parametrized in terms of two form factors, which are complex functions of q^2 only. For the case of unpolarized particles, the differential cross section has the form [6]:

$$\frac{d\sigma}{d\cos\theta} = \frac{\pi\alpha^2}{2\beta q^2}\left[(1+\cos^2\theta)|G_M|^2 + \frac{1}{\tau}\sin^2\theta|G_E|^2\right], \beta = \sqrt{1-\frac{1}{\tau}}, \ \tau = \frac{q^2}{4m^2},$$

in terms of the electric G_E and magnetic G_M form factors, where α is the electromagnetic fine-structure constant and m is the proton mass. This formula can be also written in equivalent form as [7]:

$$\frac{d\sigma}{d\cos\theta} = \sigma_0 \left[1 + \mathcal{A}\cos^2\theta\right],\ \mathcal{A} = \frac{\tau|G_M|^2 - |G_E|^2}{\tau|G_M|^2 + |G_E|^2},$$

where $\sigma_0 = \pi\alpha^2/(2\beta q^2)\left(|G_M|^2 + |G_E|^2/\tau\right)$ is the differential cross section at $\theta = \pi/2$ and $\mathcal{A}$ is an angular asymmetry which lies in the range $-1 \leq \mathcal{A} \leq 1$. Form factors can be determined from the slope and intercept of a straight line in $\cos^2\theta$, similarly to the Rosenbluth method in the space-like region. Dedicated simulations have been performed from this channel [8]: the selection of the pair of leptons in the final state is meaningful also in the first stage of the experiment, where the experiment will be limited to the low q^2 region, muons having the advantage that radiative corrections are smaller [9].

4 Prospects and Conclusions

A detailed plan for the construction of FAIR has been organized in terms of a stepwise 'Modularized Start Version' (MSV). Different phases for optimizing the physics program of $\overline{\mathrm{P}}$ANDA have been defined. Presently 'phase-0' is going on with the construction of the detectors and the use of parts in running experiments. Participations to ongoing experiments and analysis at JLab, collaboration with HADES, and MAMI allow to optimize the early program of $\overline{\mathrm{P}}$ANDA. An important aspect of 'phase-0' is the usage of the KOALA proton-recoil detector in construction and tested at Juelich. It will measure the $\bar{p}p$ elastic cross section at 90°, necessary for a precise determination of the luminosity.

In conclusion, the $\overline{\mathrm{P}}$ANDA experiment will open a new generation of high luminosity measurements with antiproton beams for a better understanding of the QCD and QED dynamics through precision studies with large data samples, measurement of widths and cross sections for hadron and hyperon spectroscopy, hypernuclei, as well as electromagnetic channels.

References

1. K. Peters, L. Schmitt, T. Stockmanns and J. Messchendorp, Nucl. Phys. News 27-3, 24 (2017) and references therein.
2. `https://fair-center.eu`.
3. `https://fair-center.eu/construction/webcam.html`.
4. `https://www.youtube.com/watch?time_continue=319&v=OzeOkrbLIQQ`.
5. [The PANDA Collaboration] B. Singh *et al.*, arXiv:1710.00684; arXiv:1704.02713 [physics.ins-det]; W. Erni *et al.* , arXiv:1207.6581 [physics.ins-det]: Eur. Phys. J. A **49**, 25 (2013); arXiv:0907.0169; arXiv:0810.1216 [physics.ins-det].
6. A. Zichichi, S. M. Berman, N. Cabibbo and R. Gatto, Nuovo Cim. **24**, 170 (1962).
7. E. Tomasi-Gustafsson and M. P. Rekalo, Phys. Lett. B **504**, 291 (2001).
8. B. Singh *et al.* [PANDA Collaboration], Eur. Phys. J. A **52**, no. 10, 325 (2016).
9. A. Dbeyssi, E. Tomasi-Gustafsson, G. I. Gakh and M. Konchatnyi, Nucl. Phys. A **894**, 20 (2012).