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The PANDA experiment: Antiproton physics at FAIR

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Summary. — The new Facility for Antiproton and Ion Research (FAIR), under construction at the GSI laboratory at Darmstadt, in a few years will make available, among different types of beams, even antiproton beams with unique features. Through a High Energy Storage Ring (HESR) for antiprotons, an antiproton beam will be available in a momentum range from 1.5 to 15 GeV/c, which will interact on a hydrogen target. The products of the interaction, including hadronic systems with strangeness and/or charm, will be detected with the PANDA magnetic spectrometer (antiProton ANnihilation at DArmstadt), and the spectroscopic analysis will allow a detailed investigation on a number of open problems of the hadronic physics, as the quark confinement, the existence of non-conventional meson states (so-called glueballs and hybrids), the structure of hadrons and of the strong interaction, with particular attention to charmonium spectroscopy. An overview of the scientific program of PANDA and the current status of the project will be presented.

PACS `13.25.-k` – Hadronic decays of mesons.
PACS `29.30.-h` – Spectrometers and spectroscopic techniques.
PACS `25.43.+t` – Antiproton-induced reactions.
PACS `21.80.+a` – Hypernuclei.

1. – Antiproton physics at FAIR

At the future facility FAIR (Facility for Antiproton and Ion Research) constructed in a few years in the site of the existing GSI laboratories at Darmstadt, within a large and multidisciplinary physics program, it will be also possible to perform studies of antiproton interactions with light nuclei.

The High Energy Storage Ring, HESR, will provide cooled beams of antiprotons with momentum of 1.5–15 GeV/c ($2.25 < \sqrt{s} < 5.47$ GeV), in two different and complementary operating modes, with luminosity and momentum resolution of $\delta p/p \sim 10^{-5}$, $L = 10^{31}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ (high resolution mode) and $\delta p/p \sim 10^{-4}$, $L = 2 \cdot 10^{32}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ (high luminosity mode), respectively.

It is known that in $\bar{p}p$ annihilation it is possible to access *in formation* on all non-exotic quantum numbers $J^{PC} = 0^{-+}, 0^{++}, 1^{--}, 1^{+-}, 1^{++}, 2^{++}$ (not just 1^- like in e^+e^-).

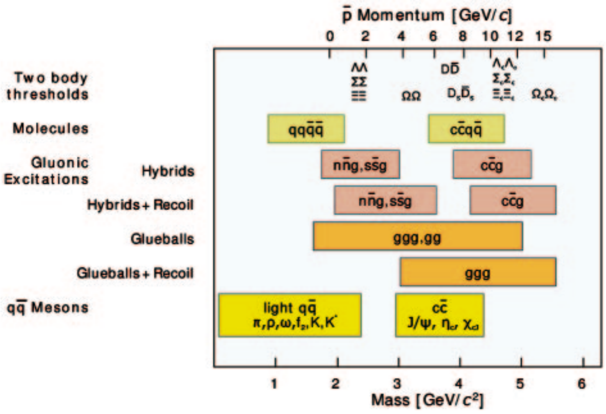

Fig. 1. – Physics topics available at PANDA.

Moreover, in the formation experiments, the measurement of masses and widths is very accurate because it depends only on the beam parameters, not on the experimental detector resolution, which determines only the sensitivity to a given final state.

So, the unique good quality of the HESR antiproton beam has suggested to perform a new experiment with a very rich hadron physics program, PANDA (antiProton ANnihilation at DArmstadt): with an interaction point located along the HESR ring, the experiment will study antiproton annihilations on hydrogen or light nuclei internal targets. In such a way, a mass resolution below 100 keV will be reached, much better than the typical values of the previous experiments (~ 240 keV).

2. – The PANDA physics program

The international PANDA Collaboration, established in 2002 and composed by more than 400 scientists from 16 countries and 53 institutions, in 2009 has collected the different items and relative simulations for its physics program in a complete PANDA Physics Performance Report [1], where all possible physical items (study of QCD bound states, non-perturbative QCD dynamics, hadrons in the nuclear medium, nuclear structure, electroweak physics) are described (see fig. 1 for a schematic view of the physics topics accessible to PANDA). Here, just a short view of some of them is presented, focusing on those connected to hadron spectroscopy.

2·1. *Charmonium spectroscopy.* – A full understanding of the states in the charmonium region is far to be reached (for a review of this topic, see ref. [2]). The eight states predicted by the potential models below the $\bar{D}D$ threshold (3.73 GeV) have been well established at the e^+e^- storage rings, at the B-factories and in $\bar{p}p$ annihilation at Fermilab. Nevertheless, the mass and width values of some of them (η_c, $\eta_c(2S)$, h_c) have still large errors and would require high-precision measurements for a better comparison with the theoretical values. Above the $\bar{D}D$ threshold, the situation is even worse: since the discovery of the $X(3872)$ in 2003, a large number of charmonium-like states, not predicted by the potential models and decaying in J/ψ, have been observed by the BELLE, BaBar and CDF experiments, but their quantum numbers are mostly unknown and their interpretation still debated [3].

PANDA will be able to contribute to the understanding of these open problems, thanks to the excellent quality of the HESR antiproton beam: at $2\cdot 10^{32}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, assuming an overall efficiency of 50% and a data taking time of 6 months/year, it will be possible to reach a total integrated luminosity of $1.5\,\mathrm{fb}^{-1}$/year, also with a momentum resolution of $\delta p/p \sim 10^{-5}$: both these values are 5–10 times better than the previous ones of Fermilab experiments. In addition, due to the higher performances of the detector (see sect. **3**) a number of different decay channels ($J/\psi \to e^+e^-$, $\mu^+\mu^-$, $\bar{D}D$, gg, hadrons $\dots$) will be accessible. Then we expect to measure with high precision the actually known states, to find missing states (*e.g.*, D states) and to understand recently discovered ones, so giving a complete picture of the dynamics of the $\bar{c}c$ system.

These perspectives are confirmed by Monte Carlo simulations of a number of physical annihilation channels, performed by the PANDA Computing group (see for example $\bar{p}p \to \eta_c(2979) \to K^0_s K^+\pi^-$ and $\bar{p}p \to D^+D^- \to (K^-2\pi^+)(K^+2\pi^-)$ presented at this Workshop [4]).

2˙2. *Open-charm physics.* – Another interesting puzzle in hadronic spectroscopy is the question of so-called open-charm states ($c\bar{q}$, D mesons), in particular the fact that some new narrow states $D_{s,J}$ recently discovered at B factories do not fit theoretical calculations.

At full luminosity and with $p_{\bar{p}} > 6.4\,\mathrm{GeV}/c$, PANDA will produce about 10^7 $\bar{D}D$ pairs/year in the $\psi(3770)$ mass region, near the $\bar{D}D$ threshold and so, despite the small signal/background ratio ($5\cdot 10^{-6}$), with very limited phase space for additional hadrons in the same process.

2˙3. *Search for exotic states.* – Also in the search for well-known exotic QCD states (glueballs gg and ggg, hybrids $\bar{q}qg$, multiquarks $\bar{q}q\bar{q}q$) PANDA could give some new answers, because, whereas in the light meson spectrum exotic states overlap with conventional states, in the $\bar{c}c$ meson spectrum the density of states is lower and the exotics can be resolved unambiguously. The lowest predicted charmed hybrids candidates, in the range 3–5 GeV, should be detected by using the "filter-action" of the $\bar{p}p$ system: all non-exotic quantum numbers are accessible in formation, but the states X_c with exotic $J^{PC} = 0^{+-}, 1^{-+}, 2^{+-}, \dots$ are accessibile in production or in associated producion ($\bar{p}p \to X_c\pi$).

2˙4. *Baryon spectroscopy.* – Little is still known about the excited states of Λ and Σ baryons, and even less about those of Ξ and Ω. A number of states in the $SU(3)$ octet and decuplet have not yet been observed, and essentially no data exist on production cross section of $\bar{p}p \to$ strange baryon-antibaryon pairs above $p_{\bar{p}} > 2\,\mathrm{GeV}/c$.

PANDA, with a total integrated luminosity of 1–2 fb^{-1}/year, should provide large quantities of $\bar{\Lambda}\Lambda$, $\Lambda\bar{\Sigma}$, $\bar{\Lambda}\Sigma$, $\bar{\Sigma}\Sigma$, $\bar{\Xi}\Xi$, $\bar{\Omega}\Omega$, $\bar{\Lambda}_c\Lambda_c$, $\bar{\Xi}_c\Xi_c$, $\bar{\Omega}_c\Omega_c$ pairs.

In addition, PANDA will have a unique opportunity to detect double $\Lambda\Lambda$-hypernuclei, in which two baryons substitute two nucleons: such hypernuclei until have been observed just in six cases. In a modified experimental setup of PANDA, it will be possible, after a threshold production $\bar{p}p \to \bar{\Xi}\Xi$, to capture Ξ^- in an atom of a secondary target in the following process:

$$\Xi^- +^A Z \to^{A+1}_{\Lambda\Lambda} (Z-1)^* + \gamma \to^{A+1} (Z+1) + \pi^-\pi^- + \gamma,$$

where the double hypernucleus formation is certified by γ-spectroscopy with Ge-detectors. It is estimated that in this way 320 double hypernuclei per day will be produced, and 8 of them will be detected.

TABLE I. – *Expected production rates at PANDA.*

Final state	Cross section	Number of reconstructed events
$\eta_c \to K_s^0 K^\pm \pi^\mp$	10 nb	10^7
$\bar{\Lambda}\Lambda$	50 μb	10^{10}
$\bar{\Xi}\Xi(\to_{\Lambda\Lambda} X)$	2 μb	10^8 (10^5)
$\psi(3770) \to \bar{D}D$	3 nb	10^7
$J/\psi(\to e^+e^-,\, \mu^+\mu^-)$	630 nb	10^9
$\chi_2(\to J/\psi + \gamma)$	3.7 nb	10^7
$\bar{\Lambda}_c\Lambda_c$	20 nb	10^7
$\bar{\Omega}_c\Omega_c$	0.1 nb	10^5

In table I an evaluation of the production rates expected at PANDA with a total integrated luminosity of 1–2 fb^{-1}/year for a few example of physics channel is shown.

3. – The PANDA detector

The PANDA spectrometer is designed to obtain the best performances for the following requests: 4π angular acceptance; high rate capability (average interaction rate 20 MHz); excellent tracking capabilities; momentum resolution 1%, vertexing capabilities for D, K_s^0 and hyperons; good particle identification for e, μ, π, K, p; γ detection up to 10 GeV; flexible and modular design for hypernuclear physics; continuous data acquisition; intelligent software trigger.

The detector is located around the HESR beam line, and is composed by a central spectrometer, which comprehends the internal target system (pellet of frozen droplet or cluster jet target of hydrogen or other gases as D_2, N_2, Ne, …), and a forward spectrometer. In fig. 2 a schematic view of the PANDA detector is shown. For a detailed description of the spectrometer see ref. [5] and references therein; here, just a short list of the subsystems is presented.

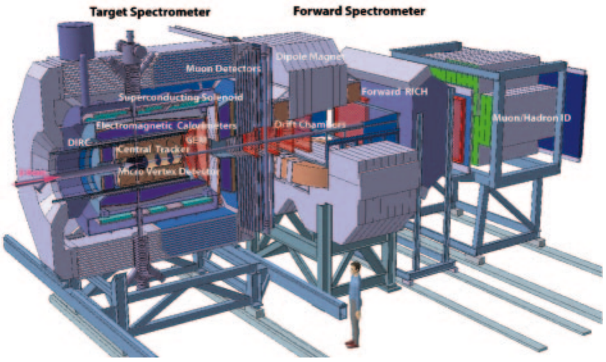

Fig. 2. – Schematic view of the PANDA detector.

The *central spectrometer*, placed in a superconducting solenoid ($B = 2\,\mathrm{T}$), surrounds the interaction region by a silicon Micro Vertex Detector (MVD, with spatial resolution of $\sim 50\,\mu\mathrm{m}$; see ref. [6] too), an inner time-of-flight detector and a cylindrical central tracker. For this tracker, two options are currently discussed: a Time Projection Chamber (TPC) and a Straw Tube Tracker (STT: see details presented at this Workshop [4]). More externally, 3 or 4 Gas Electron Multiplier (GEM) planes, a DIRC Cherenkov detector, an electromagnetic calorimeter and muon counters follow.

The *forward spectrometer*, in a deflecting dipole with a field integral of $2\,\mathrm{T}\cdot\mathrm{m}$, consists of a system of forward drift chambers (straw tubes), RICH Cherenkov detector, electromagnetic calorimeter, time-of-flight counters and hadronic calorimeter.

The tracking system, performed in the interaction region by MVD, STT/TPC and GEM combined information for the charged particles, and by the calorimeters for the neutral ones, assures high spatial and momentum resolution with a full angular coverage.

The particle identification is performed by different detectors for a momentum range from $200\,\mathrm{MeV}/c$ to $10\,\mathrm{GeV}/c$, and it is based on the different physics processes of energy loss by TPC or STT and Cherenkov radiation, respectively below and above $1\,\mathrm{GeV}/c$, and of course on time-of-flight information and electromagnetic showers.

4. – Conclusions and perspectives

The unique properties of the HESR antiproton beam, coupled with the performances of the PANDA spectrometer, will permit in the near future to significantly increase our knowledge about a number of open problems in hadron physics. Here the main topics in spectroscopy have been shortly presented: high-resolution charmonium spectroscopy in formation experiments, study of exotic states (hybrids, glueballs, multiquarks) and of strange and charmed baryons, open charm and hypernuclear physics. Other important topics that will be studied at PANDA, not described here, are the study of hadrons in nuclear matter, proton timelike form factors, crossed-channel Compton scattering, Drell-Yan processes.

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