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New physics and technical challenges of $\overline{\text{P}}$ANDA

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Abstract. An antiproton beam of unprecedented intensity and quality will soon be available at the HESR machine foreseen for the new FAIR accelerator complex of Darmstadt. This new facility, together with a properly designed new detector ($\overline{\text{P}}$ANDA), will be the ideal environment to study fundamental questions of hadron and nuclear physics and to carry out precise tests of the strong interaction.

PACS. 13.60.Le Meson production – 13.60.Rj Baryon production – 13.30.Eg Hadronic decays – 21.80.+a Hypernuclei

1 Introduction

The Gesellschaft für Schwerionenforschung (GSI) [1] of Darmstadt, Germany, is undergoing a major upgrade of the existing accelerator complex [2]. This upgrade foresees ion beams of higher intensity and better quality, and, first for GSI, an antiproton beam. At FAIR the antiprotons will be produced at the rate of 2×10^7/s and then, after accumulation and cooling, will be transferred inside the High Energy Storage Ring (HESR) for the experimental activity. The HESR machine will be equipped with an internal target surrounded by a general purpose detector: $\overline{\text{P}}$ANDA (Antiproton Annihilation at Darmstadt). The momentum of the antiprotons will vary between 1.5 and $15\,\text{GeV}/c$ so that the maximum center-of-mass energy will reach 5.5 GeV, enough for the associate production of Ω_c which is the upper limit for the mass range of charmonium hybrid predictions.

The HESR foresees two different operation modes: the high intensity mode, where with a beam momentum spread $\delta p/p$ of 10^{-4} a luminosity of $10^{32}\,\text{cm}^{-2}\text{s}^{-1}$ will be available, and the high resolution mode, where the luminosity requirement will be released to $10^{31}\,\text{cm}^{-2}\text{s}^{-1}$ to have a maximum momentum precision of 10^{-5}.

$\overline{\text{P}}$ANDA will perform a complete program of hadron spectroscopy to test many aspects of Quantum Chromo Dynamics (QCD), the generally accepted theory of strong interactions. The aim is to investigate both the dynamics of the interaction of fundamental particles, and the existence of new forms of matter such as extra charmonium states, nuclei with an explicit strange-quark content. Furthermore, particle properties, when produced inside the nuclear medium, will be studied. The importance of these measurements is related to our capability of predicting, confirming, and explaining the physical states of the theory, in other words, an exhaustive understanding of the strong-interaction mechanism.

In the past, experiments with antiprotons have proven to be a rich source of information in this field, and with the new GSI antiproton machine, all the above-mentioned topics will be addressed with a more powerful detector and dedicated experimental campaigns. $\overline{\text{P}}$ANDA will be the new general purpose detector optimized to accomplish this complete hadron physics program. In the following, the main topics of this investigation will be illustrated.

2 Hadron spectroscopy

Quantum Chromo Dynamics is extremely successful in describing phenomena at high energies where the interaction among quarks by gluon exchange can be treated by perturbation theory. Nevertheless, hadron properties cannot be directly derived from this approach, and phenomenological models, tuned on the experimental data, are used to describe lower-energy systems.

The experimental results obtained by past experiments at LEAR and Fermilab by studying $\bar{p}p$ annihilations have been excellent tools to perform hadron spectroscopy. The HESR antiprotons will allow continuation and expansion of this research field with the new possibilities offered by the higher beam intensity and the better energy resolution. Figure 1 gives an overlook on QCD-systems which could be studied in the HESR energy range.

The eight charmonium states lie exactly in the center of this mass region, and even if today all of them have been identified, open questions remain for their masses and widths. Concerning the ground state of charmonium, despite the abundance of measurements performed recently mainly at the B-factories, the knowledge of the η_c

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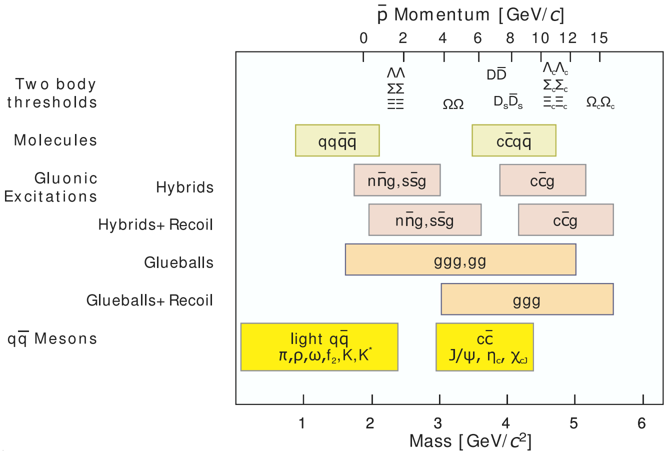

Fig. 1. QCD-systems accessible in the HESR energy range.

mass is not yet satisfactory [3]. Moreover, the different measurements of the width range between 7 and 34 MeV. New, high-precision determinations of these parameters are desirable.

The study of $\eta_c(2S)$ has just started. Discovered by the Belle Collaboration [4] it was then confirmed by CLEO [5] and BaBar [6], but the values of its mass and width are not compatible with an earlier observation of the Crystal Ball Collaboration [7]. Even the consistency with the model predictions is marginal.

The singlet-P (h_c) resonance of charmonium is of extreme importance to determine the spin dependent component of the $q\bar{q}$ confinement potential. The ${}^1P_1$ charmonium state has been discovered by the E760 Collaboration [8] that, nevertheless, could only set an upper limit for the width (< 1 MeV). Recently E835 [9] and CLEO [10] experiments confirmed the mass value quoted by E760, but the narrow width of such a state could only be measured by experiments able, like $\overline{\text{P}}$ANDA, to carry out a systematic study of its decay modes.

Concerning χ_{cJ} states, the angular distribution of radiative decays needs to be studied with high statistics, in order to clarify the discrepancies observed between the available measurements [11,12] and the theoretical predictions.

Above the $D\bar{D}$ threshold (3.73 GeV) very little is known positively. In this energy region narrow ${}^1D_2$, ${}^3D_2$ states are expected (narrow because they cannot decay to $D\bar{D}$) together with the first radial excitations of the singlet and triplet charmonium states. Actually, something unexpected in this region came out in 2003 when the Belle Collaboration reported the observation of a new narrow state with a mass of 3872.0 MeV/c^2 [13]. This new state, called X(3872), has been subsequently confirmed by other experiments, but its nature is still controversial. Speculations range from a $D^0\overline{D^{0*}}$ molecule to a ${}^3D_2$ state. All these interpretations are not satisfactory and only new data on different decay modes can shed light on the nature of this particle. The investigation of the energy region above $D\bar{D}$ threshold is a central part of the $\overline{\text{P}}$ANDA charmonium spectroscopy program. At $\overline{\text{P}}$ANDA, precise measurements would be possible thanks to the high yield of charmonium production in $\bar{p}p$ annihilation (*i.e.* BR$(\bar{p}p \to \eta_c = (1.2 \pm 0.4) \cdot 10^{-3})$). By detecting hadronic final states ($KK\pi\pi$, $4K$, 4π, $K\bar{K}\pi$, $\eta\pi\pi, \ldots$) having branching fractions two orders of magnitude higher than the $\gamma\gamma$ decay mode studied so far, high-statistic samples could be easily collected.

The spectrum of fig. 1 also indicates where "gluonic hadrons", *i.e.* hadronic systems with explicit content of glue, have been predicted by theoretical models. These states fall in two general categories; hybrids and glueballs. Hybrids consist of a quark and an anti-quark pair plus a gluon; glueballs are pure gluonic states. The additional degrees of freedom carried by the gluons allow hybrids and glueballs to have J^{PC} quantum numbers that are forbidden for ordinary $q\bar{q}$ systems. The study of exotics has been carried out systematically and intesively in the past years at LEAR, and the most promising candidates for gluonic hadrons have all been seen by antiproton-proton annihilation experiments. Two particles with exotic quantum numbers ($J^{PC} = 1^{-+}$) $\pi_1(1400)$ [14] and $\pi_1(1600)$ [15], actually discovered in pion-induced reactions at BNL, have been deeply studied in $p\bar{p}$ annihilation. Up to now, the hunt for exotic hadrons has mainly been accomplished in the mass region below 2.2 GeV/c^2; a region where a lot of broad ordinary states sit. Therefore, a precise and unambiguous identification of exotics is hardly possible. The idea of the $\overline{\text{P}}$ANDA Collaboration is to extend this search into the charmonium energy region, where only eight narrow systems are present. Up to now, LQCD calculations have been centered around the lowest-lying charmonium hybrids. Among these, three are expected to have exotic quantum numbers so that mixing effects with nearby $c\bar{c}$ states are excluded, and their identification should be easier.

Regarding glueballs, the best candidate for the glueball ground state ($J^{PC} = 0^{++}$) is the f$_0$(1500) [3] discovered in $p\bar{p}$ annihilation. However, this state mixes up with other nearby ordinary $q\bar{q}$ systems, making its exotic nature not accepted worldwide. LQCD calculations [16] make rather detailed predictions for the glueball's mass spectrum. Figure 2 shows such spectrum. In the mass range that $\overline{\text{P}}$ANDA will explore, about 15 states are predicted, some of them even with exotic quantum numbers (oddballs). The lightest oddball, with $J^{PC} = 2^{+-}$, is expected to have a mass of 4.3 GeV/c^2.

In $\bar{p}p$ annihilation, particles can be studied in two different environments: formation or production reactions. In formation reactions the $\bar{p}p$ annihilation leads to the appearance in the final state of the desired particle, while in productions reactions an extra meson ($\pi, \eta, \ldots$) is generated together with that under investigation. Formation experiments would generate exotic states with ordinary quantum numbers, while production experiments which yield an exotic together with another particle allow access to non-$q\bar{q}$ quantum numbers. From previous experiments at LEAR, we learned that production rates of exotic states are similar to those of ordinary particles. Therefore, for exotics we estimate cross-sections of formation

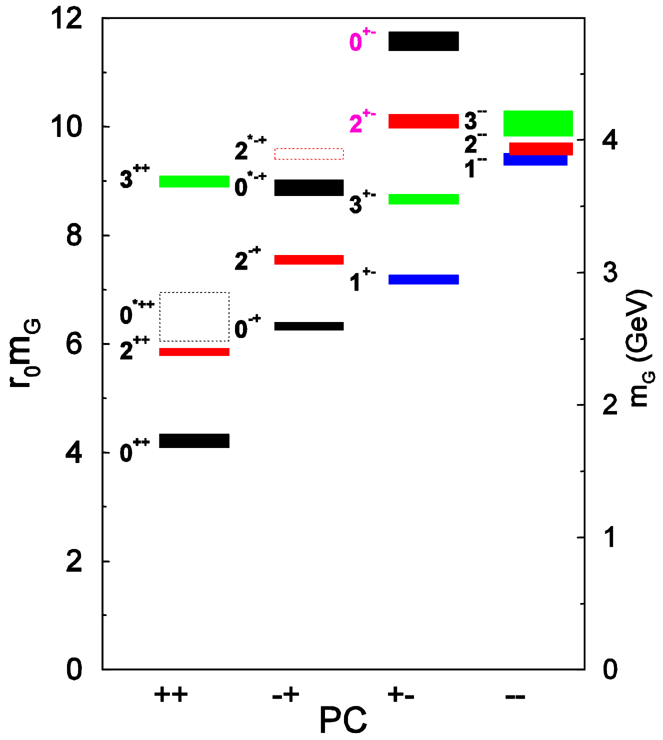

Fig. 2. Glueball prediction from LQCD calculation from ref. [16].

and of production something similar to conventional charmonium states, *i.e.* of the order of 120 pb. The $\overline{\mathrm{P}}$ANDA program for exotic search foresees to start with production measurements at the highest antiproton momentum (15 GeV/c) with the aim of studying all possible production channels of exotic and ordinary channels. The second step would consist of formation measurements by scanning the antiproton energy in small steps in the regions where promising candidates have been observed in production measurements. This will allow us to check J^{PC} assignment as well as masses and widths of the measured states.

3 Hadrons in nuclear matter

The study of the modification of hadronic properties in nuclear matter is one of the present research activities at GSI. This work is aimed at understanding the origin of hadron masses and the effect of chiral symmetry breaking on the process of mass generation. Actually, these studies, carried out on the light-quark sector [17], have showed sizeable mass splitting for both pions and kaons. A high-intensity $\bar{p}$ beam up to 15 GeV/c will allow to extend this research to the charm sector. .

For the low-lying charmonium states (η_c, J/ψ) theoretical calculations indicate [18] small in-medium mass reductions, of the order of 5–10 MeV/c^2, but since the effect is expected to scale with the volume occupied by the $c\bar{c}$ pair, the situation may change for excited charmonium states.

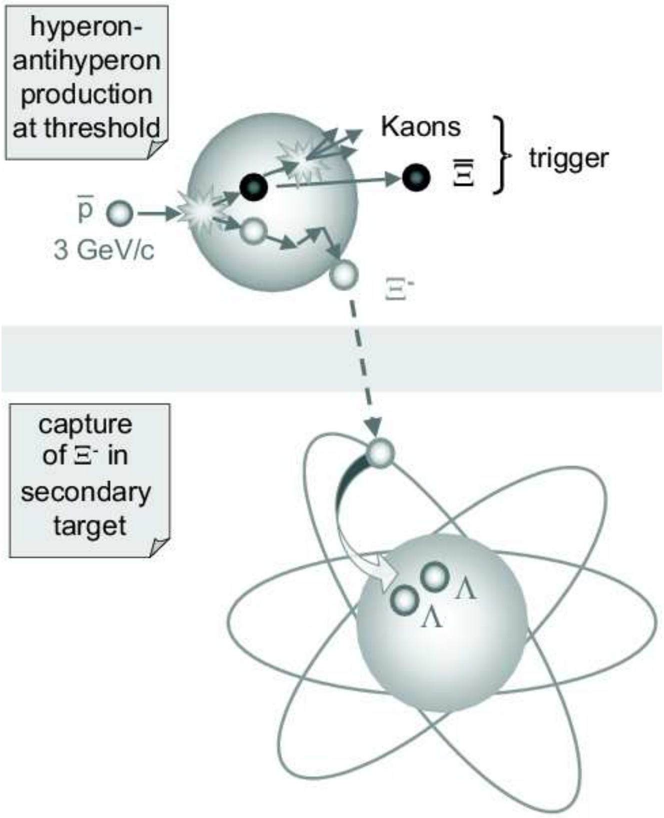

Fig. 3. The two-step reaction that will be used by $\overline{\mathrm{P}}$ANDA to produce double Λ-hypernuclei.

For the D-meson family the situation is different: made of a c-quark and of a light anti-quark, they represent QCD analogues of hydrogen atoms. Hence, they provide the unique opportunity of studying the in-medium dynamics of a system with a single light quark.

Experimentally, the study of in-medium mass modification of charmonium states will be performed measuring di-lepton decay branching ratios on different nuclear targets, whereas D-mesons will be identified via their hadronic decays to channels with kaons.

$\overline{\mathrm{P}}$ANDA will be the first experiment carrying out a systematic study of the properties of D charmed mesons, and of charmonium $c\bar{c}$ states in nuclear matter.

4 Multi-strangeness systems

Hypernuclear physics is not a new field of nuclear research but, in spite of its age, it is experiencing a renewed interest thanks to the availability of better experimental conditions that could be used to clarify some long-standing problems. One of these is the precise evaluation of $\Lambda\Lambda$-hypernuclear binding energy. Up to now, only three $\Lambda\Lambda$-hypernuclei have been detected via their double pion decay, but if they could be produced at a reasonable rate, they could be a unique source of information on Λ-Λ interactions. $\overline{\mathrm{P}}$ANDA is planning to produce copiously such systems making a $3\,\mathrm{GeV}/c$ $\bar{p}$ beam interacting with a nucleus and giving rise to a $\Xi\bar{\Xi}$ hyperon pair. The $\bar{\Xi}$ will annihilate inside the residual nucleus, and since strangeness is conserved in strong interactions, this process will produce 2 anti-kaons that could be used as a tag for the reaction. The slow Ξ^- will be captured in a secondary target, and after an atomic cascade, could interact with a proton producing two Λs that eventually could be stuck to the nucleus. For the identification and the spectroscopy of the hypernucleus, Ge-detectors will be installed. Figure 3 is illustrating schematically the two-steps process to produce $\Lambda\Lambda$-hypernuclei in $\overline{\mathrm{P}}$ANDA. Moreover, the existence of an $S=-2$ six-quark state, the H-particle [19], is another challenging topic that could be addressed studying $\Lambda\Lambda$-hypernuclei. Furthermore, one could also study the properties of the hyperatoms created during the capture process of hyperons. This will supply new information on fundamental properties of hyperons. As an example, the Ω-hyperon (sss) is particularly interesting because of its long lifetime (82 ps) and of its spin $= 3/2$. This is the only elementary baryon with a non-vanishing static quadrupole moment that therefore could be directly measured determining hyperfine splitting of Ω^- atoms.

5 Further topics

Other interesting topics could be accessed exploiting the unique features offered by the HESR machine running at full luminosity. Among those, $\overline{\mathrm{P}}$ANDA Collaboration will address new and old open questions regarding the strong interaction. A large number of D-meson pairs will be produced with antiprotons of momentum larger than $6.4\,\mathrm{GeV}/c$. B-factory experiments have discovered several particles in the D and D_s sector. It is important to verify these findings and to settle the open questions regarding the static parameters of these resonances. Threshold pair production can be employed to precisely measure the mass and the width of narrow excited D and D_s states, and to study rare decays of D-mesons, and direct CP violation.

Deeply Virtual Compton Scattering (DVCS) allows to access more details about generalized parton distribution functions. The measurements of the inverted process could provide complementary information. Furthermore, the study of Drell-Yan processes ($\bar{p}p \to l^+l^-X$) will allow access to nucleon transverse polarization functions.

Finally, in $\overline{\mathrm{P}}$ANDA the electromagnetic form factor of the proton in the time like region will be determined over the widest Q^2 range from threshold to $20\,\mathrm{GeV}^2/c^4$ and above. The high statistics collected will allow us to measure $|G_E|$ and $|G_M|$ separately.

6 The $\overline{\mathrm{P}}$ANDA detector

To investigate this wide physics program, a general purpose detector will be necessary. It should be able to deal with different targets, to cover an almost full solid angle, to identify charged and neutral particles over a wide momentum range, to be able to stand high rates ($\sim 10^7$ interaction per second), to resolve secondary vertexes, and to have a highly selective trigger system. Figure 4 shows a cross-sectional view of the detector presently under design [20]. The whole apparatus consists of a target spectrometer, surrounding the interaction region, and a forward spectrometer to detect particles emitted in the forward direction. The basic concept of the target spectrometer is a shell-like arrangement of various detectors surrounding the interaction point inside the field of a solenoidal magnet. The forward spectrometer consists of a large-gap dipole in combination with tracking detectors and calorimeters. The antiproton beam will interact with the target at the cross point with the target pipe located inside the solenoid. Both the target and the forward spectrometer will allow the detection, identification, and energy/momentum evaluation of charged and neutral particles. The combination of the two spectrometers takes into account the wide range of energies of the particles following antiproton annihilation. Furthermore, it is sufficiently flexible to make individual components exchangeable or insertable for specific measurements, *i.e.* hypernuclear measurements. In the target spectrometer, we find first a micro-vertex silicon detector, and then a charged-particle tracking system. Particle identification will be performed with a particular Cherenkov system (DIRC) similar to that constructed for the BaBar experiment. The forward region will be covered by a set of mini drift chambers and another Cherenkov detector. An electromagnetic calorimeter of about 19000 crystals will complete the setup inside the solenoid. Outside the return yoke of this magnet, muon detectors will be installed. Particles emitted with polar angles below 10° and 5° in the horizontal and vertical directions, respectively, are detected by the forward spectrometer. The current design foresees a 1 m gap dipole, tracking detectors for momentum evaluations of charged particles, a shashlyk-type calorimeter consisting of lead and scintillator sandwiches for photons detection, a hadron calorimeter and a muon detector. More details about the $\overline{\mathrm{P}}$ANDA detector can be found in ref. [20].

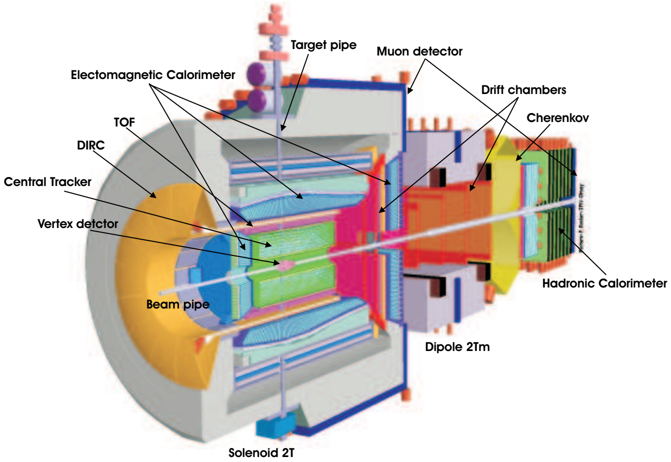

Fig. 4. Cross-sectional view of the $\overline{\mathrm{P}}$ANDA spectrometer. More details are given in the test.

7 Conclusion

After the LEAR shutdown in 1996 and the end of the Fermilab fixed target program, a new challenging project involving antiprotons is started in Europe. The characteristics of the new beam, together with the high performance of the detector involved, will determine a step forward in the hadron physics sector, allowing to continue the investigations of charmed hadrons and their interaction with matter. This will deliver unique information on many aspect of non-perturbative QCD and nuclear physics.

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