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Prospects for Hadron Physics in PANDA

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Abstract

The FAIR future facility at Darmstadt, the HESR antiproton ring and the PANDA experiment are briefly described. Some issues of the physics program of PANDA for hadron physics with antiprotons are discussed in the light of the present knowledge.

1 The Facility for Antiproton and Ion Research (FAIR)

FAIR will be an international accelerator facility constructed in the site of the existing GSI laboratories at Darmstadt. The map is shown in Fig. 1. The core of the system is a double ring synchrotron SIS100/300 with a circumference of 1100 m, that will deliver 29 GeV/c protons and heavy ions up to 35 GeV/c per nucleon for U^{92+} with unprecedented intensities. The existing GSI accelerators UNILAC and SIS 18 will serve as injectors for the new facility.

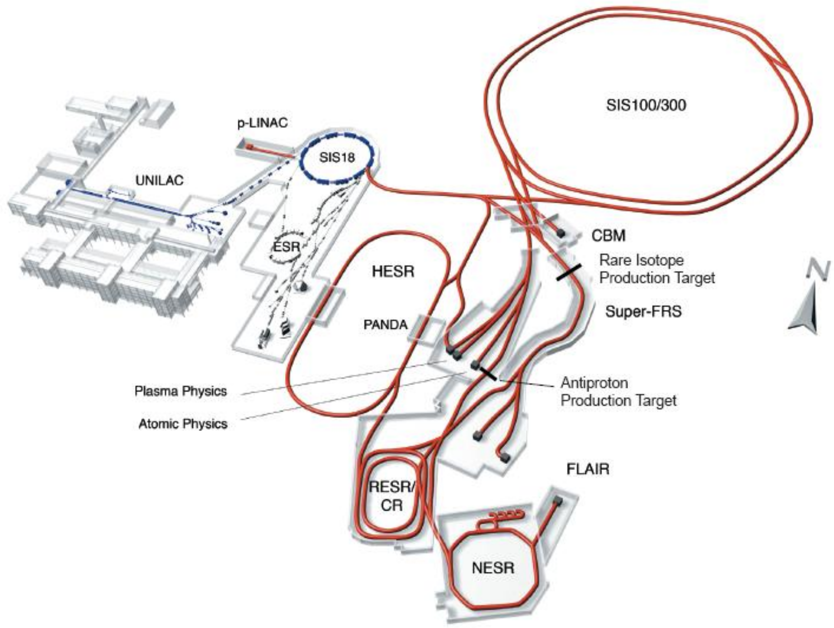

Figure 1: *The existing GSI facility (on the left) and the planned FAIR facility (on the right with the beam lines).*

The intrinsic cycle time of the accelerator and storage cooler rings will allow up to four research programs to run in full parallel mode. The multidisciplinary physics program will cover different fields: test of QCD, nucleus-nucleus collisions, nuclear structure and nuclear astroparticle investigations with nuclei far off stability, high density plasma physics, atomic and material science studies, radio-biological and other applicative researches.

The High Energy Storage Ring (HESR) will allow QCD studies with cooled beams of 1.5-15 GeV/c ($2.3 < \sqrt{s} < 5.5$ GeV) antiprotons with momentum resolution down to $\delta p/p \simeq 10^{-5}$, corresponding to a beam energy spread less than 30 keV, about a factor ten better than the previous machines.

The perspective of this antiproton beam of exceptionally good quality has motivated the formation of the PANDA Collaboration (antiProton ANnihilation at DArmstadt, 15 countries, 47 Institutes, about 370 scientists) with the aim to perform a wide hadron physics program. [1)]

2 The PANDA detector

PANDA can be considered the next generation experiment in hadron physics. It is designed to fulfill many highly demanding requirements: the detector must have 4π angular coverage, high momentum resolution on charged particles (1%), full neutral and charged particle identification, high rate compatibility (10^7 annihilations/s), good vertex resolution (better that 100 μm), high magnetic field, modularity and flexibility. [1]

The general layout of PANDA is based on two magnetic spectrometers and is shown in Fig. 2.

The target will be either a stream of small pellets of frozen hydrogen (pellet target) or a homogeneous gas stream (cluster jet target). Both options are under test; in any case, the chosen solution must assure a luminosity up to $L = 2 \cdot 10^{32}$ cm^{-2} s^{-1} when in the HESR ring there are 10^{11} circulating particles. [2]

The interaction region is placed in a superconducting solenoid which provides an axial field of 2T. The interaction point is surrounded by a silicon Micro Vertex Detector (MVD), which has five barrel shaped layers plus five disk-shaped detectors in the forward direction. The three innermost layers are composed of pixel detectors for the optimal detection of secondary vertices (with resolution $\simeq$ 100 μm) and maximum acceptance close to the interaction point. The identification of low momentum particles will be possible via $\mathrm{d}E/\mathrm{d}x$.

The MVD is surrounded by a cylindrical tracker. Two options are currently discussed, a Straw Tube Tracker (STT) consisting up to 28 layers of self supporting straws and a Time Projection Chamber (TPC) with an ungated charge collection based on a Gas Electron Multiplier (GEM) readout. The TPC is technically more complicated, but offers less material and a better particle identification via $\mathrm{d}E/\mathrm{d}x$.

The next detector is a Cherenkov counter based on the DIRC principle, consisting of quartz rods in which the light is internally reflected to an array of photon detectors in backward directions. Various types of readout (photomultipliers, APD) are under study and the details can be found in ref. [1]

An electromagnetic calorimeter consisting of about 20,000 crystals read by APD is placed outside the DIRC. As detector material $PbWO_4$ is under study, since it is faster than BGO, although with a worse light output. Finally,

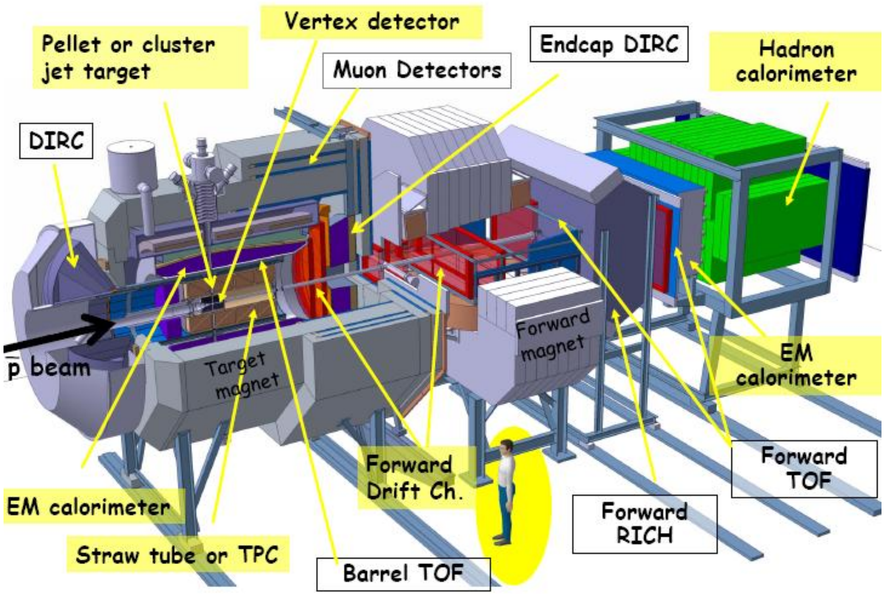

Figure 2: *The PANDA apparatus*

outside the central magnet and its iron return yoke, drift tubes are placed to detect the muons exiting the spectrometer. A time of flight detector in the central region is also under study, to detect low momentum particles.

In the forward direction a series of mini drift chambers is used to track particles entering in the forward spectrometer, which is based on a dipole with a field integral of 2 Tm. The system accepts particles emitted forward below 5^0 and 10^0 in the horizontal and vertical directions, respectively.

The option of a third Cherenkov detector, based on gas or aerogel is still under investigation. In addition, a time of flight detector is considered for charged particle identification.

A forward electromagnetic calorimeter will also be used, based on lead-scintillator sampling and fiber readout, with a resolution within 3-5%$/\sqrt{E}$ (GeV). A study is under way on the use of the refurbished MIRAC (from WA80) as a hadron calorimeter placed after the electromagnetic calorimeter.

To provide maximum flexibility, a hardware trigger is not foreseen. The readout electronics will perform intelligent data reduction, to transfer only the physically relevant information. All data will be marked by a timestamp by

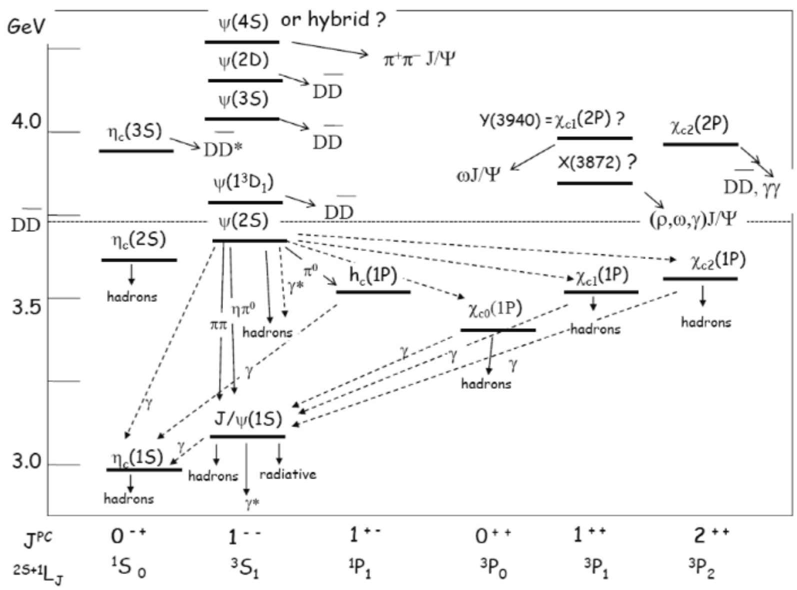

Figure 3: *The charmonium system and its transitions*

which event building can be performed at a later stage.

3 The PANDA physics program

3.1 Charmonium spectroscopy

Large scale simulations of QCD on discrete Euclidean space-time volumes show that the gluonic flux tube that connects two infinitely heavy color sources at a given distance can be well approximated by a potential. Because of the high value of the c-quark mass ($m_c \simeq 1.5\text{GeV/c}^2$) this quark-antiquark potential is essentially non relativistic ($\beta \simeq 0.2$), with some relativistic corrections [3].

The potential models predict eight states below the $D\overline{D}$ threshold of 3730 MeV (see fig. 3), with masses in agreement with the measurements within less than 1% [4]. The BaBar, BES, BELLE and CLEO-c experiments are producing a lot of high precision results on the masses of these charmonia and new data on their widths and decay modes. However, spin singlets can not be directly produced in e^+e^- annihilation and their population via electromagnetic transitions from the vector states is either suppressed (for η_c, η_c') or C-forbidden (for h_c). In the η_c case, hindered M1 transitions distort the resonance line shape in a non trivial way. [5] Hence, data on singlet masses and widths of accuracy comparable with that of the other mesons are still missing; for example, the error on the $\eta_c(2S)$ width is 50% (14 ± 7 MeV [6]).

On the other hand, in $p\overline{p}$ annihilation all the hyperfine levels of Fig. 3 can be populated more or less with the same intensity. For example, the cross section of $\sigma(p\overline{p} \to \eta_c) \simeq 500$ nb [1], compared with $\sigma(e^+e^- \to e^+e^-\eta_c)$ which is of the order of pb [7]. With an antiproton beam the masses and widths of all states can be measured very accurately, being determined only by the parameters of the accelerator. In this case the detector has to be optimized for the selection of the final state and for an efficient background rejection. Many high precision results on spin singlets and on χ_c spin triplets in P wave have been obtained in this way by the E835 and E760 Fermilab experiments. [6, 8]

The high luminosity, the beam energy resolution of HESR and the high performances of the PANDA detector will allow to continue and to extend these measurements of resonance formation by performing scans in step less than 1 MeV. Leptonic modes will be detected in parallel to the radiative and hadronic ones.

The mass region above the $D\overline{D}$ threshold is still poorly known. Only 5 states have been identified of the 32 $c\overline{c}$ states predicted by the potential models [4] in the energy range $3 \leq E \leq 4.5$ GeV. In addition, many surprising and unexpected states are emerging from the high statistics samples of CLEO-c [5], BaBar [10] and BELLE [9].

There are several theoretical and experimental investigations of the nature of these states. Their interpretations as glueball, hybrids or multiquark states are numerous (see ref. [11]) and many of them have been presented at this Conference. We quote only the $Z(4430)$ meson [9, 12], that is the first charmonium-like charged state, a property consistent with a $[qu\overline{Q}\overline{d}]$ multiquark structure.

All the predictions indicate that the lowest energy charmed hybrids ($c\overline{c}g$) states have masses between 3.9 and 4.5 GeV/c^2, including the spin exotic state 1^{-+}. The glueball spectrum extends to 5 GeV/c^2, with the lightest 2^{+-} spin exotic meson (oddball) at 4.3 Gev/c^2. The identification of these states requires high statistics to perform reliable spin-parity analyses. Favorable decay channels would be $\phi\phi$ or $\phi\eta$, which are easily distinguishable in PANDA from others annihilation channels.

In the search of these exotic states PANDA can exploit the filter action of the $p\overline{p}$ system: all the states with non-exotic quantum numbers are accessible in formation, J^{PC} exotic states X_c as $0^{+-}, 1^{-+}, 2^{+-}$ are accessible in production or in associated production processes as $p\overline{p} \rightarrow \pi X_c$. The expected cross sections range from hundreds of pb for the associated production [13] up to some nb, so that in PANDA one expects $10^2 - 10^5$ of such events per day.

3.2 Open-charm physics

The open charm $c\overline{q}$ states, called D mesons, are usually described in terms of different potential models deduced from charmonium studies or from effective lagrangians with chiral and heavy quark symmetries [4].

The announcement [14] of a very narrow $D_s(2317)$ low mass state seen in the $D_s\pi^0$ decay mode and lying approximately 160 MeV below the calculations of the majority of models, has renewed the interest in open charm spectroscopy. Another narrow state is the $D_s(2460)$, [14, 15] which lies below most model predictions. Mass predictions near to the experimental values are obtained from a tetraquark $|c\overline{s}(u\overline{u} + d\overline{d}) >$ model [16].

The HESR running with full luminosity at laboratory momenta larger than 6.4 GeV/c can be considered a factory for tagged open charm. The accelerator will produce about 10^7 D meson pairs per year in the $\psi(3770)$ mass region. The background conditions are expected to be favorable for PANDA, because the charm hadrons will be produced at threshold without phase space for other hadrons in the same process. These conditions will allow the detailed study of the structure of the rich spectrum of the D mesons and of their dominant and rare decays.

3.3 Antibaryon-baryon production in $p\overline{p}$ annihilation

The quark rearrangement and the annihilation and creation of quark-antiquark pairs can be studied in a particularly clean way in the $p\overline{p} \rightarrow Y\overline{Y}$ baryon-antibaryon production process. In the absence of polarization, the angular distribution of the final products of the reaction can be written as:

$$I(\theta_i, \theta_j) \propto 1 + \alpha P_Y + \overline{\alpha} P_{\overline{Y}} + \alpha\overline{\alpha} \sum_{i,j} C_{ij} \cos\overline{\theta_i} \cos\theta_j \ ,$$

where $i, j = x, y, z$ and α is the decay asymmetry parameter. The angles refer to the decay directions in the $Y, \overline{Y}$ rest frame. This distribution has been extensively studied for the $p\overline{p} \to \Lambda\overline{\Lambda} \to p\pi^-\overline{p}\pi^+$ reaction by the PS185 experiment at the LEAR accelerator of CERN. [17] The study of the polarization and of the spin correlation coefficients C_{ij}, showing that the $s\overline{s}$ pairs are predominantly produced with parallel spin, put severe constraints to the quark-gluon and meson exchange models, whereas the depolarization coefficient data from a polarized target do not match at present with any model. [17].

The magnitude of the polarization of the Y and $\overline{Y}$ must be the same if CP invariance holds, with $\alpha_Y = -\alpha_{\overline{Y}}$. Consequently, one can define the parameter $A_{Y\overline{Y}} = (\alpha_{\overline{Y}} + \alpha_Y)/(\alpha_{\overline{Y}} - \alpha_Y)$ that should be zero if CP is conserved. The average value of A in the case of the $p\overline{p} \to \Lambda\overline{\Lambda}$ reaction is $A_{\Lambda\overline{\Lambda}} = 0.006 \pm 0.014$ [17] which is lower than what is quoted in PDG (0.012 ± 0.021) [6]. The discovery of a CP violation in the hyperon decay would be the first observation in a baryonic system. The effect is expected to be smaller than 10^{-4} [17].

These topics can be further studied in PANDA and extended to doubly strange and charmed hyperons. Nothing is known experimentally on the $p\overline{p} \to Y_c\overline{Y}_c$ reactions. For example, it would be very interesting to investigate whether the creation of a $c\overline{c}$ pair in the $p\overline{p} \to \Lambda_c^+\overline{\Lambda_c^+}$ reaction will show the same features as the $s\overline{s}$ creation in the $\Lambda\overline{\Lambda}$ case.

For the channels with only charged particles in the final state, the overall reconstruction efficiency is around 20%. [1] The production cross sections are orders of magnitude greater than those from e^+e^- annihilation and a number of reconstructed events/month from 10^4 to 10^9 is expected for the production of $\Lambda_c\,\overline{\Lambda}_c$ and $\Lambda\,\overline{\Lambda}$ pairs, respectively.

3.4 Drell-Yan processes

In Drell-Yan processes $p\overline{p} \to l^+l^-X$ the angular distribution of dileptons, for the unpolarized case is:

$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = \frac{3}{4\pi}\frac{1}{\lambda+3}\left(1 + \lambda\cos^2\theta + \mu\sin^2\theta\cos\phi + \frac{\nu}{2}\sin^2\theta\cos 2\phi\right) ,$$

where θ and ϕ are defined in the rest frame of the lepton pair. In the simple parton model, one would get $\lambda = 1$ and $\nu = \mu = 0$. At leading-order (LO) and next-to-leading-order (NLO), perturbative QCD calculations produce $\lambda \simeq 1$ and $\mu \simeq \nu \simeq 0$ (for a discussion see ref. [18]).

On the other hand, a series of experiments on high energy collisions of pions and antiprotons with various unpolarized nuclei reported a largely asymmetric azimuthal distribution, namely $\lambda \simeq 1$ and $\mu \ll \nu \simeq 30\%$, with $1-\lambda-2\nu$ large and negative. [19]

This can be interpreted as a genuine non-perturbative effect, relating the size of ν to the Boer-Mulders distribution $h_1^\perp$, which describes how in an unpolarized hadron the momentum distribution of a parton is distorted by its transverse polarization. This distribution, belonging to the family of chiral-odd parton densities, is not observable in fully inclusive deep inelastic scattering and for this reason at present it is unknown.

In $p\bar{p}$ collisions, $h_1^\perp$ for valence quarks appears at leading twist level; the generated observable asymmetry allows to study spin-orbit correlations of transversely polarized partons even using unpolarized beams and targets. Monte Carlo simulations for Drell-Yan $p\bar{p} \to \mu^+\mu^- X$ reactions show that in a reasonable running time (one month) some 10^4 events with an azimuthal asymmetry up to 10% can be produced for the unpolarized case. [18]

3.5 Time-like proton form factors

The electric and magnetic proton form factors G_E and G_M can be connected to the lepton angular distribution of the $p\bar{p} \to e^+e^-$ reaction through the one-photon exchange QED formula:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = \frac{\alpha^2}{4\beta_p\, s}\left[|G_M|^2(1+\cos^2\theta) + \frac{4m_p^2}{s}|G_E|^2\sin^2\theta\right] ,$$

where θ is the CM angle between the electron and the proton and β_p is the CM proton velocity. Data at high $Q^2 = s$ are crucial to test the onset of the asymptotic scaling region of perturbative QCD, where the space-like and time-like form factors should become equal. In this region the contribution of the electric term is suppressed. For this reason, due to the limited statistics at high momenta, up to now $|G_E|$ and $|G_M|$ have not been measured separately and have been determined with the assumption $|G_E| = G|_M|$.

One of the goals of PANDA will be to make angular distribution measurements with high statistics and full angular coverage to measure the magnitude of the two form factors separately from threshold up to 20-25 $\mathrm{GeV}^2/\mathrm{c}^4$. Most of these measurements could be performed in parallel with other programs, avoiding resonance peaks in order to reduce systematic uncertainties.

3.6 Further options

A study of charmed mesons in nuclear matter will be performed in PANDA, by replacing the jet target with wires of various materials. These studies will explore the partial restoration of the $\langle q\bar{q}\rangle$ chiral symmetry in nuclear matter and can be considered equivalent to the Higgs searches in electroweak theory.

In the case of charmonium, multigluon exchange should generate an attractive potential between a $c\bar{c}$ meson and a nucleon, with a binding energy of the order of 10 MeV [20], giving measurable effects on the charmonium by shifting its mass and increasing its width. Here the difficulty is to select final states, as e^+e^-, carrying the unperturbed information outside the nuclear medium. In PANDA some hundreds of such events per day are expected on a Carbon target. [21]

The magnitude of the J/Ψ nucleon absorptive cross section is essential to interpret the J/Ψ suppression as a signal for the formation of the quark-gluon plasma formation. It can be measured by the accurate scanning of the $\overline{p}A \rightarrow J/\Psi + (A-1)$ reaction between 3.5 and 4.5 GeV/c.

Recent GSI experiments have shown that charged pions and kaons exhibit effective masses in the nuclear medium different from those in vacuum. [22] This effect is due to the quark condensates and is an important input for qq and $q\bar{q}$ potential models. A similar behaviour is predicted also for the open charm mesons D^+ and D^- but it has not yet been observed. PANDA could make this observation for the first time, measuring with high accuracy the shifting of D^-/D^+ masses and of the $D\overline{D}$ production threshold in nuclear matter.

The investigation of hypernuclei requires the modification of the PANDA vertex region. [1] One of the most interesting topics is the study of double-Λ hypernuclei that can be produced using the two step reaction:

$$\overline{p}(2.6\,\mathrm{GeV/c}) + \mathrm{A} \rightarrow \Xi^-_{\mathrm{slow}} + \overline{\Xi^-}_{\mathrm{trigger}}\,; \qquad \Xi_{\mathrm{slow}} + \mathrm{A}' \rightarrow_{\Lambda\Lambda} \mathrm{A}' + \ \gamma'\mathrm{s}\ .$$

As a secondary active target (A') high resolution solid state micro tracking detectors will be used and a position sensitive Ge-γ array will allow high rate spectroscopy. One can estimate a rate of 14 500 stopped Ξ^- in ^{12}C nuclei per day and, taking into account the PANDA acceptance on hypernuclear events [1], a rate of 320 produced $\Lambda\Lambda$ hypernuclei per day is expected.

Finally, the large amount of data collected by PANDA will also allow the study of rare channels with cross sections of the order of pb. Among these, the most interesting are probably the $p\bar{p} \to \gamma\gamma$ annihilation, which should give complementary information on Generalized Parton Distributions, rare D decays as $D^+ \to \mu^+\nu$ to test LQCD calculations, and the D^+/D^- decay ratios to detect direct CP violation in Cabibbo-suppressed decays.

4 Conclusions

The charmonium and open charm spectroscopy challenge our understanding of QCD. The field is evolving in an interesting and exciting way, and, on the experimental side, this will require many years (perhaps decades) of intense experimentation to find mass, width, decay modes and spin-parity of all the states. In this field, many relevant contributions from antiprotons and PANDA are expected.

The $p\bar{p}$ annihilation tests quark rearrangement and quark-gluon dynamics. The production of baryon-antibaryon pairs is copious and with PANDA it will be possible to extend these studies also to the charm sector.

The production of Drell-Yan lepton pairs in $p\bar{p}$ annihilations is one of the best ways to investigate the internal hadron structure and in particular the quark spin-orbit correlations. The particle identification capabilities and the hermeticity of PANDA will play a crucial role in collecting high statistics clean samples of data.

Many other issues of hadron physics are accessible to PANDA and have been briefly described here. The unique properties of the HESR $\bar{p}$ beam, coupled with the performances of PANDA, will play a leading role for the hadron physics with antiprotons in the near future.

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