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QCD physics at hadron storage rings: From COSY to FAIR

JAMES RITMAN
Institut für Kernphysik, Forschungszentrum Jülich, 52425 Jülich, Germany
E-mail: j.ritman@fz-juelich.de

Abstract. As a result of the rapid rise of the coupling constant α_s at low momentum transfers, perturbation theory is not an appropriate method to describe the strong interaction. In this kinematic regime other methods such as lattice QCD or effective field theories are more appropriate to investigate the appearance of a still unsettled phenomena: confinement and chiral symmetry breaking. Furthermore, the confinement of quarks and gluons to hadrons allows crucial tests of fundamental symmetries that are inherent to the QCD Lagrangian but are broken in hadronic systems. Thus, high precision measurements of the production and decay of specific hadronic states provides decisive benchmarks to investigate the properties of QCD in this regime. A new series of experiments are being prepared using nearly full acceptance detectors for neutral and charged particles around internal targets in high intensity, phase-space-cooled hadronic beams. Later this year, it is planned to transfer the WASA detector from the CELSIUS to the COSY ring in order to measure the production and various decay channels of the η and η' mesons, thereby investigating the violation of P, C, T, and combinations thereof, as well as isospin violation. The experimental and theoretical techniques employed here will provide an important basis to extend these investigations to the static and dynamical properties of hadrons with charm quark content with the high energy storage ring for antiprotons at the new GSI/FAIR facility. Additional related perspectives will be opened at the new facility ranging from the properties of hadrons in dense nuclear matter to measurements of the nucleon's transverse spin distribution in the valence quark region using polarized antiprotons.

Keywords. Antiprotons; charmonium; D mesons; eta mesons; new facilities.

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1. Introduction

QCD at low and moderate energies is still the least understood corner of the so-successful Standard Model. It is characterized by confinement of quarks and gluons and the broken chiral symmetry in the light quark sector as well as the heavy quark symmetry for the c- and b-quarks.

One of the yet-to-be-understood phenomena in QCD is color confinement. The fundamental constituents of strongly interacting matter – quarks and gluons – only appear as colorless bound states, called hadrons. This feature of QCD hinders a direct access to the quark-gluon dynamics at low energies and one is thus forced to draw indirect conclusions though the observation of more complex composite systems. Nowadays various roads are followed to improve our understanding of QCD at low energies. Besides *ab initio* lattice QCD calculations, that are still hampered with serious conceptual and computational problems, one considers precision spectroscopy and high accuracy studies of pion, eta and kaon dynamics. The results of the former can be interpreted either through QCD inspired models, that promise insight, e.g., into the structure of confinement but may also allow to disentangle molecular states from compact quark states, or be compared to the results of lattice QCD. The latter have a direct connection to QCD through the spontaneously and explicitly broken chiral symmetry that strongly constraints the dynamics of its (pseudo)-Goldstone bosons like pions, kaons and etas and their interactions with matter fields, like e.g. nucleons. A striking example is the QCD mass term, that contributes to and links the isospin breaking in πN scattering and the proton–neutron mass difference. Also, the sector of the c- and b-quarks can be systematically analysed using heavy quark and soft collinear effective field theories.

Both these issues are the subject of an upcoming program of experiments utilizing hadron beams. Results with unprecedented statistical precision will be achieved due to the high cross sections involved in the hadron-induced reactions. Furthermore, the internal experiments will achieve relative mass resolutions on the order of $\sigma_M/M \approx 10^{-5}$ due to highly efficient phase space cooling of the circulating beam. Additional related perspectives will be opened at the new facility ranging from the properties of hadrons in dense nuclear matter to measurements of the nucleon's transverse spin distribution in the valence quark region using polarized antiprotons. The planned programs are presented in the following sections.

2. Hadron physics at COSY with proton and deuteron beams

The future hadron physics program at COSY, conducted by IKP and the COSY users, addresses:

- *Investigation of symmetries and symmetry breaking* (*isospin I*, *C*, *CP*, *and CPT*). As outlined in the corresponding proposal [1] this will be the primary physics objective of WASA at COSY:
  - Studies of η and η decays, which are abundantly produced in proton–proton interactions.
  - Isospin violation in $dd \to \alpha\pi^0$ with polarized d-beam; in this case the spin–isospin filter mechanism in hadronic reactions is essential.
- *Hadronic spectroscopy and reactions*. A confirmation or a disproof of the existence of the pentaquark $\Theta^+(1540)$ is of great interest and will be pursued with high priority, using the TOF set-up and a newly built polarized frozen spin target. If the $\Theta^+(1540)$ is shown to exist, a model-independent determination of its parity is only possible at COSY.
- *Spin physics*. A detailed understanding of nucleon–nucleon scattering at least at a phenomenological level up to high energies is very desirable.

> While EDDA has improved the proton–proton database, spin-observables in neutron–proton scattering is very incomplete above 800 MeV, resulting in large uncertainties in the isoscalar phase shifts. Many of these holes can be filled by internal COSY experiments using a polarized deuterium beam or deuterium target, e.g. at ANKE.

The first of these topics which addresses investigations of symmetries and symmetry breaking which will be performed with the WASA detector is discussed in more detail in the following. For other aspects of the COSY physics program, refer to the paper by H Machner in these proceedings.

The WASA detector (wide angle shower apparatus) is currently installed at the CELSIUS facility, which is formed from the old ICE ring at CERN, in the Svedberg Laboratory (TSL), Uppsala, Sweden. This 4π detector was built in the 1990s by a Swedish–Polish–German–Russian–Japanese collaboration with the aim of studying rare reactions and decays. After the end of the experimental programme at CELSIUS in summer 2005, the device will be relocated to COSY at the Forschungszentrum Jülich (FZJ), Germany.

While CELSIUS delivers maximum beam momenta of 2.1 GeV/c, COSY offers significantly higher momenta up to 3.7 GeV/c with polarized and phase-space-cooled proton and deuteron beams, thus well above the threshold for η' production in pp interactions. WASA is a large acceptance detector for neutral and charged ejectiles from hadron-induced interactions. Almost any final state of pN, pd and dd reactions can be detected with large efficiency, resulting in a major expansion of the experimental potential both of WASA and COSY, where a photon detector has been missing up to now. The WASA target consists of a beam of frozen hydrogen or deuterium pellets of about 25 μm diameter, allowing luminosities of up to $10^{32}/\text{cm}^2/\text{s}$ in interactions with the circulating beam in COSY.

The η and η' decays that vanish in the limit of equal-light quark masses (for example, $\eta' \to \eta\pi\pi$) allow the exploration of explicit isospin symmetry-breaking in QCD. Furthermore, precision measurements of rare η and η' decays can be used to obtain new limits on the breaking of the charge, parity and time symmetries or their combinations. Further topics for WASA will be searches for and investigation of (crypto-) exotic hadrons, such as the light scalar mesons $a_0(980)$ and $f_0(980)$. Pentaquarks like the Θ^+ and hyperon resonances like the $\Lambda(1405)$ can be studied with precise measurements of decay chains and couplings to other hadrons.

Another promising process where precise measurement can confront theoretical predictions is the isospin-violating process $dd \to {}^4\text{He}\pi^0$. Pioneering measurements of this reaction have already been performed at the Indiana Cooler. At COSY such studies can be extended to higher energies and, in particular, to the reaction $dd \to {}^4\text{He}\pi^0\eta$ which should be driven by the isospin-violating $a_0 - f_0$ mixing.

With WASA at COSY one can reach a luminosity at least an order of magnitude larger than was previously available at CELSIUS. This means a production rate of more than 10^6 mesons per day with subsequent hadronic, radiative, leptonic and forbidden decays that can be detected by WASA. The expected event rates will substantially increase world statistics for decays of mesons and a precise testing ground for symmetry breaking in hadronic systems will be available. Issues like C-, P-, T-, isospin- and $SU(3)$-symmetry breaking, the pseudo scalar mixing angle, and the structure of hadrons will be addressed.

The WASA at COSY project is a common effort of many institutions. The collaboration currently comprises 137 members from 24 institutes in seven countries. WASA will be shipped to the Forschungszentrum Jülich in autumn 2005 and the experimental program is expected to start in the beginning of 2007.

3. Hadron physics at FAIR

The science goals underlying the international FAIR project span a broad range of research activities, addressing essentially all aspects of the structure of matter, from the quark-gluon structure of hadrons to the physics of astronomical objects like novae and supernovae [2]. Related to the various hierarchical levels of matter, FAIR will, at the same time, touch upon key aspects in the evolution of the universe, such as phase transitions of hadronic matter and nucleosynthesis in stars and star explosions. Specific research programs that will be pursued at the FAIR facility comprise:

- Investigations with beams of short-lived radioactive nuclei, addressing questions about nuclei far from stability; areas of astrophysics and nucleosynthesis in supernovae and other stellar processes, as well as tests of fundamental symmetries.
- Studies of hadronic matter at the sub-nuclear level with beams of anti-protons, focussing on two key aspects: confinement of quarks and the generation of the hadron masses. They are intimately related to the existence (and spontaneous breaking) of chiral symmetry, a fundamental property of the strong interaction.
- Studies of compressed, dense hadronic matter in nucleus–nucleus collisions at high energies. Here, the focus will be on investigations in the vicinity of the tri-critical point of the QCD phase diagram as well as on medium modifications of charmed mesons in dense hadronic matter.
- Investigations of bulk matter in the high-density plasma state, a state of matter of interest for inertial confinement fusion and astrophysical settings.
- Studies of quantum electrodynamics (QED), of extremely strong electromagnetic fields, and of ion–matter interactions.

The concept and layout of the FAIR accelerator project has evolved from the science requirements as follows: substantially higher intensities are achieved, compared to the present system, through faster cycling and, for heavy ions, lower charge state which enters quadratically into the space charge limit. The reduced charge state, and still a desired energy of up to 1.5 GeV/u for radioactive beam production, requires a larger magnetic bending power. These aspects are fulfilled by the SIS100 synchrotron. It also generates intense beams of energetic protons, up to 30 GeV, from these antiprotons. Heavy-ion beams of high energy up to 35 GeV/u for the heaviest beams are generated using ions in a high charge state plus the somewhat slower but still rapidly cycling SIS300 synchrotron ring. The intensity required for these beams allows for long extraction times. Similarly, the SIS300 can be used as a stretcher ring for radioactive beams. Both, primary and secondary beams can be injected, cooled and stored in a system of rings with internal targets and in-ring experimentation. Rings may be shared while using different beams.

Based on the developments and excellent experiences with cooled beams at the present GSI facility, the future program will broadly take advantage of this aspect of beam handling. This applies in particular for the physics program associated with the storage cooler rings NESR and HESR, where fast electron and stochastic cooling at medium and at high energies will be essential for experiments with exotic ions and with antiprotons. In order to achieve the required luminosities in the antiproton storage ring HESR magnetized electron cooling at high energies (8 MeV) is necessary, which represents a main technical challenge.

GSI, together with the involved science communities, has recently developed a technical plan for a staged construction of the new facility. Following that plan, the construction of the new facility, i.e. general planning, civil construction and technical installation of the accelerators and experiments, is divided into three stages:

- With regard to technical installations, the first stage (starting from the year 2005 until 2010) comprises an upgrade of the existing SIS 18 synchrotron as well as the installation of the Super-Fragment Separator and the storage rings CR/NESR for exotic ion beams.
- SIS 100 and the high energy antiproton storage ring HESR will be installed in the second stage (from the year 2008 until 2013/14).
- In the third stage (from the year 2010 until 2014/15), SIS 300 and the related experimental areas will be built.

After completion of each stage new user communities can commence their research programs.

3.1 *High energy storage ring*

The HESR at FAIR is a storage ring for high quality beams in the momentum range from 1.5 to 15 GeV/c [3]. It will provide anti-proton beams to explore hadron structure and quark-gluon dynamics. An important feature of the facility is the combination of phase-space-cooled beams and internal targets (e.g. at PANDA) which will allow experiments of unprecedented precision. The HESR combines demanding requests for high intensity beams with challenging requirements in two modes of operation: high luminosity and high resolution, respectively.

To meet these boundary conditions, the following requirements have to be taken into account in the HESR design:

- Low impedance and large dynamic aperture of the ring;
- Highly efficient anti-proton injection and accumulation schemes;
- High accuracy and stability of beam parameters;
- Small beam sizes at the interaction points with the internal targets;
- Strong beam cooling systems for long life-times of the stored beam and to provide a high luminosity.

Key tasks for the design are:

- A technical design study, followed by prototyping of critical elements for the high energy electron cooling system: the electron-cooling system is a necessary prerequisite for the antiproton physics with dense internal targets. It serves two purposes:
  - Initial electron cooling of the injected beam, in order to reach the conditions for the internal-target experiments.
  - Continuous electron cooling in order to counteract beam heating from the internal target and from intra-beam scattering and other effects.

  Development of new highly sensitive pick-up systems which fulfil the low impedance requirement of HESR and the higher band-width: the injected HESR beam has to be first reduced in size which is done by stochastic cooling systems with optimised band-width (4–8 GHz) up to final HESR energies.
- A combination of electron and stochastic cooling seems necessary to achieve the user demands. Electron cooling is favoured for pre-cooled HESR beams to reach a very small momentum spread together with luminosities of about 10^{31}/cm/s. The maximum anti-proton momentum for which electron cooling is required constitutes a critical parameter which will affect the performance considerably.
- A feasibility study of a multi-harmonic RF cavity.
- Design and prototyping of (curved) super-conducting magnets and cryostats is of utmost importance to realize the HESR lattice.

The HESR is designed as a racetrack-shaped storage ring with a maximum magnetic bending power of 50 Tm. The storage ring will cover an area of about 120 $\times$ 250 m with a circumference of 574 m, including two 132 m long straight sections. One of these sections will be mainly used for the installation of an internal target in combination with a large detector system. The detector concept requires a strong solenoid field and large aperture dipole magnets for the separation of secondary particles at small laboratory angles. The opposite long straight section is used for beam injection, beam acceleration and electron cooling. In addition, a stochastic cooling system for transverse and longitudinal cooling is foreseen which has to be installed at the entrance and exit of the straight sections. The latter has to be designed to allow for experiments with either high momentum resolution of about 10^{-5} at reduced luminosity or at high luminosity up to 2×10^{32}/cm/s with enlarged momentum spread. Special requirements for the lattice are dispersion-free straight sections for the experiments and imaginary transition energy to avoid longitudinal instabilities.

For the design and construction of the HESR, a consortium under the leadership of IKP (Prof. R Maier) has been founded, which bundles resources and expertise of GSI, TSL (Sweden) and IKP. This consortium submitted the *Technical Report on the HESR* in January 2005, which describes the design, construction, commissioning, and important R&D work for the facility. As stated above, IKP will be the leading laboratory for building the HESR.

3.2 *Hadron spectroscopy with antiproton annhilation at PANDA*

The PANDA experiment, located at an internal target position of the high energy storage ring for anti-protons is one of the large installations at the future FAIR facility [4]. It is being planned by a multi-national collaboration, currently consisting of about 350 physicists from 48 institutions in 15 countries. The PANDA detector is designed as a multi-purpose setup that allows to cover a wide-ranged program in hadron physics which is accessible in the study of anti-proton–proton collisions at anti-proton momenta from 1.5–15 GeV/c. The cornerstones of the PANDA physics program were already presented in the approved FAIR Conceptual Design Report (CDR):

- Study of narrow charmonium states at so far unprecedented precision;
- Search for gluonic excitations such as hybrids and glueballs in the charmonium mass region;
- Properties of mesons with hidden and open charm in the nuclear medium;
- Spectroscopy of double strange hypernuclei.

Further options are spectroscopic studies of mesons with open charm, search for CP violation in the $\Lambda\overline{\Lambda}$ system or the neutral $D\overline{D}$ system, and studies of the proton structure (crossed-channel Compton scattering, Drell–Yan processes, time-like form factor).

In order to cope with the variety of final states and the large range of particle momenta and emission angles, associated with the different physics topics, the detector has almost 4π detection capability both for charged particles and photons. It is divided into two sub-components, a central target spectrometer and a forward spectrometer with an overall length of 12 m of the total detector. The cylindrical structure of the target spectrometer is given by the 2 T solenoid magnetic field around the target. In sequence of increasing radii, it consists of a micro vertex detector (MVD) as the innermost sub-detector close to the interaction point, a central tracker built either of straw tubes (STT) or a time projection chamber (TPC) in the barrel part and mini-drift chambers (MDC) as front cap, a system of ring-imaging Cherenkov detectors for particle identification, an electromagnetic calorimeter made of $PbWO_4$ crystals, a superconducting coil, and a muon detector outside of the return yoke. The forward spectrometer consists of a 2 Tm dipole magnet with a set of multi-wire drift chambers (MDC) for tracking, a RICH detector for particle identification, electromagnetic and hadronic calorimeters for neutral and charged particles, and a muon detector as the most downstream component.

The central tracking devices provide the basis to measure hadrons with open charm quark content, and thus are described is some more detail here.

The MVD is essential for the detection of displaced decay vertices of hadrons with open charm or strangeness. Its design faces various challenging requirements that have to be fulfilled simultaneously:

- good vertex resolution of between 20 and 40 μm,
- high granularity to limit the occupancy of the innermost layers,
- low material budget to reduce multiple scattering and photon conversion,
- low power consumption,

- good time resolution, and
- high radiation hardness.

In the current design, the MVD consists of a barrel part with five layers and a forward part with five disks where the interior layers (three in the barrel part and two in the front part) are built of pixel detectors and the remaining outer layers are made of double-sided strip detectors. As the baseline solution for the pixel detectors, the hybrid concept of the ATLAS or CMS design is being considered. The evaluation of the performance of the ATLAS front-end chips confronted with the requirements of PANDA has already started.

The central tracker volume extends from 15 cm to 42 cm radius, and from 40 cm upstream of the interaction point to 110 cm downstream along the beam axis. Due to its expertise gained in the development of the straw tube detector of the TOF experiment, the IKP is well-prepared to contribute substantially to the development of the STT in PANDA which is the baseline option for the technology of the central tracker. In the current design the STT consists of 11 double layers of 150 cm long straw tubes which allows for a spatial resolution of 150 mm in the x- and y-directions, whereas the z-resolution of a few mm is achieved by tilting some of the layers by about $\pm 2^{\circ}$. Since the concept of using a tilt angle has however several drawbacks, as an alternative option to achieve z-information, double-sided read-out with charge division and/or time difference measurement is being pursued.

3.3 *Transversity functions with PAX*

Polarized anti-protons provide access to a wealth of single- and double-polarization observables, thereby opening a new physics window at HESR: for example it allows a first measurement of the transversity distribution of the valence quarks in the proton [5].

The PAX collaboration has proposed a scenario to provide polarized anti-protons at FAIR, using a dedicated polarizer ring, a second cooler synchrotron ring and the HESR, culminating in its final stage in an asymmetric proton–anti-proton collider.

The proposed detector consists of a large-angle apparatus optimized for the detection of Drell–Yan electron pairs. A dedicated low-energy anti-proton polarizer ring (APR) yields an anti-proton beam polarization of $P = 0.3$ to 0.4 after about two beam life-times (of the order of 5–10 hours).

- By using an internal hydrogen gas target and a detector installed in a 3.5 GeV/c cooler synchrotron ring (CSR), the Phase-I experimental program could start in 2014, completely independent of the operation of the HESR.
- In Phase-II, the CSR serves as an injector for the polarized anti-protons into the HESR. A chicane system inside the HESR is proposed to guide the high-energy anti-proton beam to the PAX detector, located inside the CSR straight section. In Phase-II, fixed-target or collider anti-proton–proton experiments over a broad energy range become possible.
- In the collider mode, polarized protons stored in the CSR up to a momenta of 3.5 GeV/c are bombarded head-on with 15 GeV/c polarized anti-protons

stored in the HESR. This asymmetric double-polarized anti-proton–proton collider is ideally suited to map e.g. the transversity distribution in the proton.

Although this proposal was not part of the original FAIR Conceptual Design Report, it could be an ideal way for the transition from COSY to HESR on a longer time-scale, since it could imply an actual movement of COSY to FAIR to become the CSR.

3.4 *Nuclear matter studies with CBM*

The SIS300 accelerator at the new FAIR facility will also be able to deliver beams of all nuclear species with energies up to 35 A·GeV, thereby allowing the properties of highly compressed baryonic matter as it is produced in nucleus–nucleus collisions to be investigated [6]. The goal here is to explore the QCD phase diagram in the region of moderate temperatures but very high baryon densities. The envisaged research program includes the study of key questions of QCD such as confinement, chiral symmetry restoration and the nuclear equation of state at high densities. The most promising diagnostic probes are vector mesons decaying into dilepton pairs, strangeness and charm.

The major experimental challenge is posed by the extremely high reaction rates of up to 10^7 events/s. These conditions require unprecedented detector performances concerning speed and radiation hardness. The detector layout comprises a high resolution silicon tracking system in a magnetic dipole field for particle momentum and vertex determination, ring imaging Cherenkov detectors and transition radiation detectors for the identification of electrons, an array of resistive plate chambers for hadron identification via TOF measurements, and an electromagnetic calorimeter for the identification of electrons, photons and muons. The detector signals are processed by a high-speed data acquisition and trigger system.

4. Summary

The behaviour of the strong interaction in the low momentum, strong coupling domain is one of the least well-tested regions of the Standard Model. Further, significant progress in this sector is expected by investigating the static and dynamical properties of hadrons, in particular those with charm quark content, with high precision and resolution. A new series of experiments are upcoming using hadronic beams to perform such investigations with unsurpassed rates and resolution.

Tests of symmetries and symmetry breaking is the primary objective of the project to relocate the WASA detector from CELSIUS to the COSY accelerator. This facility will be able to surpass the existing world statistics on many sensitive decay channels of the η and η' mesons within days to weeks of running time. This experiment is expected to be up and running by the beginning of 2007.

On a somewhat longer time horizon, the new facility FAIR will offer multifaceted opportunities to investigate hadronic properties using antiproton and heavy-ion beams. Hadron spectroscopy studies will be performed with the PANDA experiment at the higher energy storage ring that will provide phase-space-cooled antiprotons of unsurpassed quality and luminosity. Further measurements of the nucleon's transversity distribution in the valence quark region are envisioned. Finally, the properties of (charm) hadrons in a dense nuclear environment will be investigated using heavy-ion reactions leading to a system of high net baryon density at moderate temperatures.

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