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Antiproton physics at GSI: Studying the physics of hadronic matter

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Abstract. GSI/Darmstadt is planning a major upgrade of its accelerator and experimental facilities. One of the main components of the proposed GSI-upgrade is a storage ring, in which beams of antiprotons with unprecedented quality and intensity will be available with beam momenta up to 15 GeV/c. At this facility a wide physics program is planned to investigate the structure of hadrons in the charmonium mass range, with the goal to develop a better understanding of the transition from quarks and gluons to hadrons as effective degrees of freedom. An overview of the physics program and the detector system envisioned for this project are presented.

PACS. 13.75.-n Hadron-induced low- and intermediate-energy reactions and scattering (energy $\leq$ 10 GeV) – 25.43.+t Antiproton-induced reactions

1 Introduction

Quantum Chromodynamics (QCD) is generally accepted to be the correct theory to describe the interaction of particles via the strong force. In systems involving large momentum transfers, corresponding to small-distance scales, perturbative methods can be applied, thereby allowing high-precision tests of the theory. However, with decreasing momentum transfers, corresponding to increasing length scales, the magnitude of the strong-coupling constant increases to the point that the perturbative treatment is no longer valid. In this low-energy regime the structure of the hadrons is characterized by new unsettled phenomena:

– As a result of the rapid rise of the coupling constant, free quarks are not observed at length scales larger than the size of the nucleon, instead, quarks are bound to color neutral objects, called hadrons.
– The mass of hadrons is much larger than the sum of their valence quark masses. This is related to the interaction of the hadron with the complex structure of the QCD vacuum.
– The self-interaction of gluons should permit hadrons with valence quarks and gluons (so-called hybrids) and states of nearly pure glue (*i.e.* glueballs) to exist.

These properties are inherent in the specific nature of the strong force and are the objects of our attempts to understand the nature of multi-particle states bound by the strong force.

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2 Hadron physics with antiproton beams

Experimental studies of hadronic structure can be performed with various probes such as electrons or antiprotons. The interaction of electrons with hadrons provides the advantages of using a point-like probe that interacts via the well-known —but relatively weak— electromagnetic force. On the other hand, antiproton annihilation produces copious numbers of particle-antiparticle pairs in a gluon-rich environment, allowing spectroscopic studies with unprecedented statistics and precision. Antiprotons in the 1–15 GeV/c range are thus an ideal tool to study the questions mentioned above. Intense discussions within the international hadron physics community have been distilled into a physics program. This physics program, together with a facility to produce high-luminosity, cooled antiproton beams up to 15 GeV/c, has been included in the conceptual design report for the planned upgrade of the GSI-Darmstadt facility [1,2].

The physics program at the planned GSI facility includes the following main aspects:

- Charmonium spectroscopy: precision measurements of mass, width, decay branches of all charmonium states, especially to extract information on quark confinement.
- Firm establishment of the QCD-predicted gluonic excitations (charmed hybrids, glueballs) in the charmonium mass range (3–5 GeV/c^2).
- Search for modifications of meson properties in the nuclear medium, and their possible relationship to the partial restoration of chiral symmetry for light quarks. Particular emphasis is placed on mesons with open and hidden charm in order to learn more about the origin of hadron masses.
- Precision γ-ray spectroscopy of single and double hypernuclei for information on their structure and on the hyperon-nucleon and hyperon-hyperon interaction.

With increasing luminosity of the antiproton facility further possibilities will emerge. These include D-meson decay spectroscopy (rare leptonic and hadronic decays), the search for *CP* violation in the charm and strangeness sector (D-meson decays, Λ-$\overline{\Lambda}$ system), the extraction of generalized parton distributions from $\bar{p}$-p annihilation, and fundamental physics with stopped antiprotons.

The use of an antiproton beam allows several major advantages to study the physics program outlined above. For instance, antiproton beams can be cooled (stochastically and/or with electron cooling) to obtain momentum resolutions of the order of 10^{-5}. Furthermore, charmonium states of all quantum numbers can be directly formed, in contrast to e^+e^- reactions where only the vector states (*i.e.* $J^{PC} = 1^{--}$) could be directly formed. The possibility to measure charmonium states in formation reactions[1] allows the resolution of the mass and width to be limited only by the beam momentum (because of 4-momentum conservation). In contrast, the resolution of the mass and width in production reactions[2] is limited by the detector resolution which is on the order of 10^{-2}. Moreover, the possibility to measure both production and formation reactions is also a very important tool for the spin-exotic search, *i.e.* a particle that appears in production reactions but not in formation reactions is an interesting candidate. The large branching ratio to baryon-antibaryon pairs also is a useful tool, *e.g.* using the $\bar{\Xi}$ to tag a Ξ beam which is incident on a secondary target, as forseen in the double-hypernuclei program.

3 Proposed experimental facility

The antiproton beams needed to pursue the physics program outlined above will be produced by a primary proton beam from the planned fast-cycling, superconducting 100 Tm ring. The antiprotons will be collected with a rate of about 2×10^7/s and then stochastically cooled and stored. After 5×10^{10} antiprotons have been produced, they will be transferred to the High-Energy Storage Ring (HESR) where internal experiments in the momentum range 1.5–15 GeV/c can be performed. Stochastic cooling in the HESR ring will allow a beam momentum resolution of $\delta p/p \sim 10^{-4}$ at luminosities up to $2\times10^{32}/\mathrm{cm}^2/\mathrm{s}$. For antiproton momenta below 8 GeV/c electron cooling will enable a higher momentum resolution ($\delta p/p \sim 10^{-5}$) at a reduced luminosity $10^{31}/\mathrm{cm}^2/\mathrm{s}$.

To serve the many experiments planned at this new facility, a general purpose detector is planned. This detector facility must be able to handle high rates (10^7 annihilations/s), with good particle identification and momentum resolution for γ, e, μ, π, K, and p. The experiments will use internal targets, *i.e.* either pellets of frozen H_2 or cluster jet targets for the reactions on proton targets, and wires for reactions on nuclear targets.

The proposed detector is comprised of a target spectrometer which has a 2 T solenoidal magnetic field, and a forward spectrometer that uses a 1 m gap dipole magnet with 2 Tm bending power. A schematic overview of the target spectrometer is given in fig. 1. The innermost detector is a microvertex detector (MVD) for precise measurements of particles produced at secondary vertices. The MVD will be a radiation hard silicon pixel detector, based on the design for LHC experiments [3,4]. A cylindrical array of straw tubes for tracking (STT) will surround the MVD. Particles at small polar angles will also be measured by a sequence of mini drift chambers (MDC) of the HADES type [5,6] located downstream of the target.

Kaon-pion discrimination will be performed with two types of ring imaging Čerenkov counters. For polar angles above 22°, the detection of internally reflected Čerenkov (DIRC) light [7] is used. The radiator will be constructed out of 1.7 cm thick quartz slabs. At smaller polar angles we plan to use proximity focusing Čerenkov counters similar to those in STAR/ALICE [8]. An important part of the detector is the electromagnetic calorimeter. In order to realize the desired compact structure and high-rate capability,

[1] Single-particle intermediate state, *e.g.* $\bar{p} + p \to \chi_{c1}$.

[2] Multi-particle intermediate state, *e.g.* $e^+ + e^- \to \gamma + \chi_{c1}$.

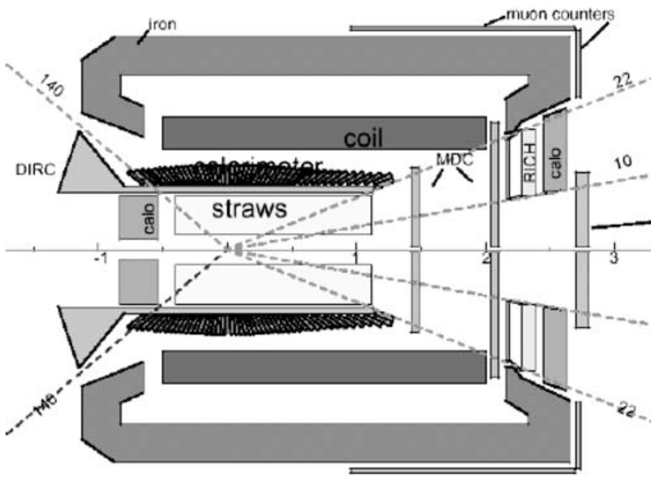

Fig. 1. Schematic overview of the detector concept for the planned HESR antiproton facility at GSI.

scintillators of the $PbWO_4$ type are very advantageous. Experiments using phototubes for readout show that they have good energy resolution for γ/e-detection [9]. Outside the iron yoke of the solenoid magnet the target spectrometer has two arrays of 72 scintillator strips for muon detection.

4 Simulations of the detector performance

The properties of the proposed detector system have been investigated extensively during the past year. All the main components of the target spectrometer are implemented in a simulation package based on the GEANT4 software [10]. The results of this simulation were analyzed with a software package based on ROOT [11], and the event generator is based on the package PLUTO++ [12].

To be able to examine reactions involving D-mesons a vertex resolution on the order of 100 μm is required. The simulations indicate a vertex resolution of about 50 μm in the transverse and 80 μm in the longitudinal direction.

The momentum resolution has been investigated at several polar angles as a function of transverse momentum. Typical transverse-momentum resolutions are 1-2%. Furthermore, the momentum resolution has been investigated by reconstructing events from the reaction $\bar{p}p \to J/\Psi + \phi$ at $\sqrt{s} = 4.4$ GeV/c^2. Gaussian fits to the $\mu^{\pm}$ and $K^{\pm}$ invariant-mass distributions, have widths of 36 and 3.6 MeV/c^2 for the J/Ψ and ϕ, respectively.

The DIRC provides information on the velocity of particles, thus by combining this with the momentum measurement from the tracking, the mass of the particle can be determined. Above about 0.6 GeV/c the efficiency to identify a kaon is over 95% and the probability to misidentify a pion as a kaon is about 1%.

The electromagnetic calorimeter is used to measure photon energies and to provide electron-hadron separation. The simulations indicate that the calorimeter has sufficient resolution to reconstruct the η-meson with about 20 MeV/c^2 resolution. Furthermore, the probability to misidentify a pion as an electron is on the order of 10^{-3}.

The muon counters are located outside of the solenoid magnet. The integrated efficiency of the muon counters is about 90% for muons above 1.3 GeV/c. In the most relevant momentum range the misidentification probability for pions to be registered as muons is between 1% and 2%.

The geometrical acceptance times the efficiency for detection and reconstruction of the target spectrometer has been investigated by simulating the reaction $\bar{p}p \to J/\Psi + \phi$ at $\sqrt{s} = 4.4$ GeV/c^2. The total acceptance times efficiency was determined for both dilepton decay branches of the J/Ψ as a function of the cosine of the J/Ψ center-of-mass polar angle. The acceptance is large ($\approx$ 50%) and quite uniform over the full allowed region, which is very important in order to perform accurate partial-wave analyses.

5 Summary

The annihilation of antiprotons on protons and nuclear target provides experimental access to a wide range of important questions in the non-perturbative range of QCD. The collisions of antiprotons with nuclei allow charm-nucleus interactions to be studied, which extend naturally the present program of GSI on the properties of hadrons in nuclear matter.

The simulations of the detector concept show its ability to measure electrons, muons, pions and kaons over a large phase space region. A momentum resolution of 1-2% is obtained and we have a high discriminating power for particle identification. Combining these features with the large solid-angle coverage (which is close to 4π) allows the application of strong kinematical constraints to the data which will serve for a high level of background suppression. One of the open question concerns the feasibility of a pellet target system. The forward spectrometer and the Ge array for the hypernuclei experiments still need to be included into the simulations.

The project described here has recently taken a big step forward in the approval process: The German Scientific Council has evaluated the proposals for a number of planned large research facilities in Germany and has recommended that the planned GSI upgrade should be funded when certain conditions are fulfilled [13]. Currently a collaboration is forming in order to develop a detailed technical proposal for the design and construction of the detector system presented here.

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