NEW PERSPECTIVES FOR ANTIPROTON PHYSICS THE HESR-PROJECT AT GSI*

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Outstanding questions of Quantum Chromodynamics in the non-perturbative regime are discussed. A research program addressing these questions is outlined. This program is based on the availability of antiproton beams of unprecedented quality and intensity at the planned future accelerator facility at GSI Darmstadt. The physics potential of this project and the accelerator and detector concept are presented.

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1. Introduction

When we analyze the matter which surrounds us with ever increasing resolution a hierarchy of different structures becomes apparent: molecules, atoms, atomic nuclei, nucleons, and quarks. The first three systems have two general features in common: the constituents of these systems have all been seen as free particles, like free electrons or nucleons. Secondly, the mass of these systems is equal to the sum of the constituent masses, apart from binding energy corrections which are on the percent level. For the nucleon a completely different situation is encountered. From deeply inelastic lepton scattering we know that the nucleon has a substructure of quarks and gluons but no one has ever seen free quarks; they are confined within the nucleon. We know that the quarks inside the nucleon have masses of only a few MeV/c^2 but the mass of the nucleon is 938 MeV/c^2. These questions address the central outstanding issues of hadron physics:

(i) How are hadrons (baryons and mesons) built from quarks and gluons?
(ii) What determines the mass of hadrons?
(iii) Can Quantum Chromodynamics (QCD), the theory of the strong interaction, quantitatively account for the confinement of quarks within hadrons?

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QCD is extremely successful in describing high energy processes like jet production at high energies, *i.e.* when one probes the interaction among quarks at very short distances. The key to this success is the small coupling constant $\alpha_s \approx 0.1$, which allows perturbation theory to be applied. At much larger distances comparable to the size of the nucleon, this approach breaks down as the coupling strength approaches 1. This energy regime is characterized by typical non-perturbative phenomena like confinement, the fact that quarks are not observed as free particles but bound within hadrons, and chiral symmetry breaking, the breaking of a fundamental symmetry of QCD which occurred in the early Universe when quarks coalesced to form hadrons. This is where the intellectual challenge is: to explore QCD in the non-perturbative regime both experimentally and theoretically. On the theoretical side enormous progress has recently been made by Lattice QCD calculations and by developing field theoretical models.

The essential difference to other field theories is that gluons, the mediators of the strong interaction, themselves carry color charge. Therefore, they not only interact with quarks but also among themselves. As a consequence, systems consisting of gluons, so called glueballs should exist. The selfinteraction among gluons also leads to the formation of so called flux tubes between quarks which generate a force of about 10 t which is almost independent of the distance between the quarks. As a result, quarks cannot be further separated from each other, qualitatively accounting for their confinement within hadrons. The goal, however, is to achieve a quantitative description of these phenomena.

2. The research program

Detailed discussions of these fundamental questions within several working groups have led to the formulation of a hadron physics research program at the High Energy Storage Ring (HESR) which is part of the proposal for an extension of the accelerator facility at GSI [1-5]:

(i) The most promising way to learn more about confinement is charmonium spectroscopy, the study of the bound system of a charm and an anticharm quark. The $c\bar{c}$ spectrum is analogous to that of positronium and can be calculated to a large extent by perturbation theory; deviations, in particular in the higher lying states can be traced to confinement effects.

(ii) Glueballs and hybrids resulting from the gluon self-interaction are the most characteristic features of QCD and should be identified. Here, the search for heavy glueballs and charmed hybrids ($c\bar{c}g$) is particularly promising because less mixing with normal mesonic modes is to

be expected in this higher mass range (3–5 GeV/c^2). The mixing of gluonic modes with scalar mesons in the 1.5–2.2 GeV/c^2 mass range has so far prevented an unambiguous identification of glueball states.

(iii) Studying the masses of charmed mesons (D-mesons) in the nuclear medium is an extension to the charm sector of the ongoing research program at GSI where medium modifications of light mesons like pions and kaons are being studied. These experiments aim at clarifying the origin of hadron masses.

(iv) Adding strangeness to nuclei opens up a new degree of freedom in nuclear spectroscopy which is complementary to ongoing and planned nuclear structure studies with exotic beams.

(v) Further possibilities which are envisaged once the full luminosity has been achieved, include the study of inverted deeply virtual Compton scattering to find a complementary access to generalized parton distributions within the nucleon, the study of CP-violation in the D and Λ sector where physics beyond the Standard Model might be found, the investigation of rare D-decays, and fundamental symmetry tests with antiprotons stopped in a trap.

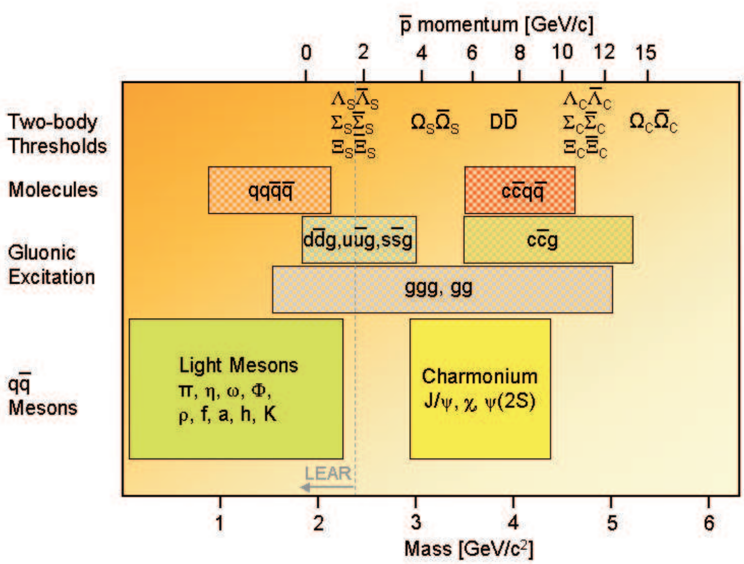

Fig. 1. Expected masses of $q\bar{q}$–mesons, glueballs, hybrids, molecular quark configurations, and particle–antiparticle production thresholds. The corresponding momenta of antiproton beams, required for the production of these QCD-systems, are also indicated. The figure is taken from [1].

The mass and momentum range for these investigations are shown in Fig. 1. The hadronic systems of interest like charmonium ($c\bar{c}$), glueballs (ggg), charmed hybrids ($c\bar{c}g$) and the D-meson threshold are indicated. As some phase-space above threshold is needed, $\bar{p}$-momenta up to 15 GeV$/c$ are required.

In the following subsections, the different research topics are outlined in more detail.

2.1. Charmonium spectroscopy

Determining the interaction potential of bound systems through precision spectroscopy has been a successful tool at all levels of the structural hierarchy of matter, as for example in atoms and molecules. The fundamental understanding of strong interactions in terms of QCD was greatly stimulated by the 1974 discovery of J/Ψ, the vector state ($J^{PC} = 1^{--}$)

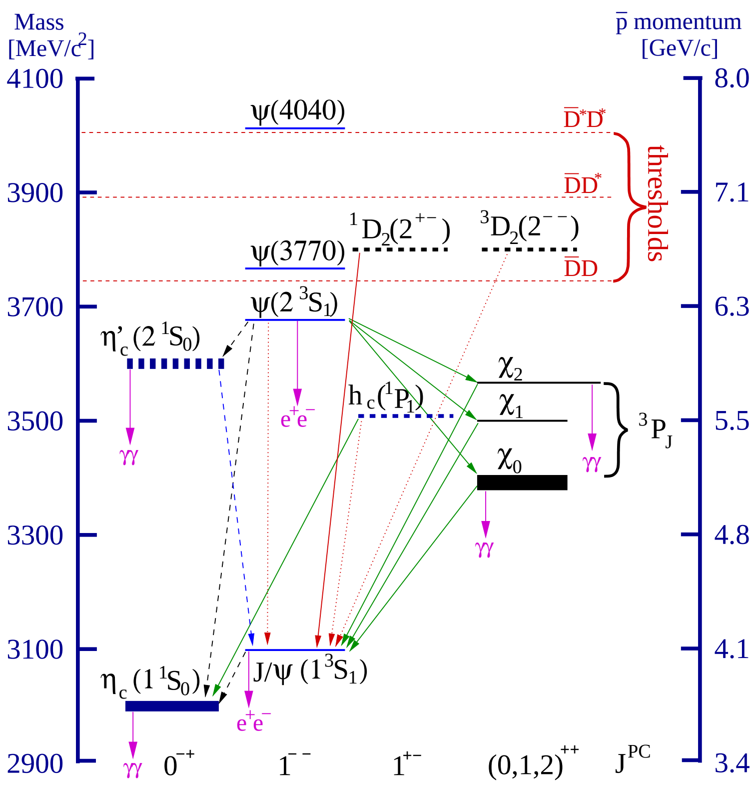

Fig. 2. Charmonium states and their decay modes. Poorly known states are marked by dashes. The figure is taken from [1].

of the bound charm quark and charm antiquark system ($c\overline{c}$). In this mass range, the strong coupling $\alpha_s \approx 0.3$ is sufficiently small to justify application of perturbative QCD, but the charm quark mass is not sufficiently large to completely suppress non-perturbative corrections. Charmonium is thus an optimum testing ground for studying the interplay of perturbative and non-perturbative effects and for a quantitative understanding of confinement.

Although many experiments at e^+e^- colliders and more recently at Fermilab in $\overline{p}p$ collisions provided many measurements of charmonium states, widths and branching fractions, many open questions remain [6] which will be addressed by the GSI charmonium program. This includes the search for the still uncertain η_c' state [7], the confirmation of the $^1P_1$-state which is important for a determination of a possible spin dependent part of the confinement potential, and in particular the identification of states above the $D\overline{D}$ threshold, a mass range where very little is known, where, however, one encounters the highest sensitivity to the parameters of the confinement potential.

2.2. The search for heavy glueballs and charmed hybrids

The QCD spectrum is much richer than the naive quark model. Since gluons, which mediate the strong force between quarks, can also interact among themselves, new types of hadrons can be formed: glueballs and hybrids. Glueballs are excited states of almost pure glue, while hybrids are states consisting largely of a quark, an antiquark, and excited glue. The additional degrees of freedom carried by gluons allow glueballs and hybrids to have spin-exotic quantum numbers like $J^{PC} = 0^{--}, 0^{+-}, 1^{-+}, 2^{+-}$ that are forbidden for normal mesons. Exotic quantum numbers provide the easiest way to distinguish gluonic hadrons from $q\overline{q}$ states, but even non-exotic glueballs and hybrids can be identified by measuring an overpopulation of the experimental meson spectrum and by comparing their decay modes, masses and quantum numbers with Lattice Quantum Chromodynamics calculations (see Figs. 3,4) and model predictions.

The identification of gluonic modes in the mass range of 1–2 GeV/c^2 has so far been hampered by the large number of about 100 normal $q\overline{q}$ states in this range. With only eight, narrow charmonium states in the 0.8 GeV/c^2 region below the $D\overline{D}$ threshold and a relatively smooth continuum above, there are good chances to identify and resolve gluonic modes unambiguously in this mass range which will become accessible at the new GSI facility. Recent experiments at LEAR have demonstrated that particles with gluonic degrees of freedom are copiously produced in $\overline{p}p$ annihilation, demonstrating that $\overline{p}$ beams are the most promising probe for addressing this important aspect of strong interaction physics.

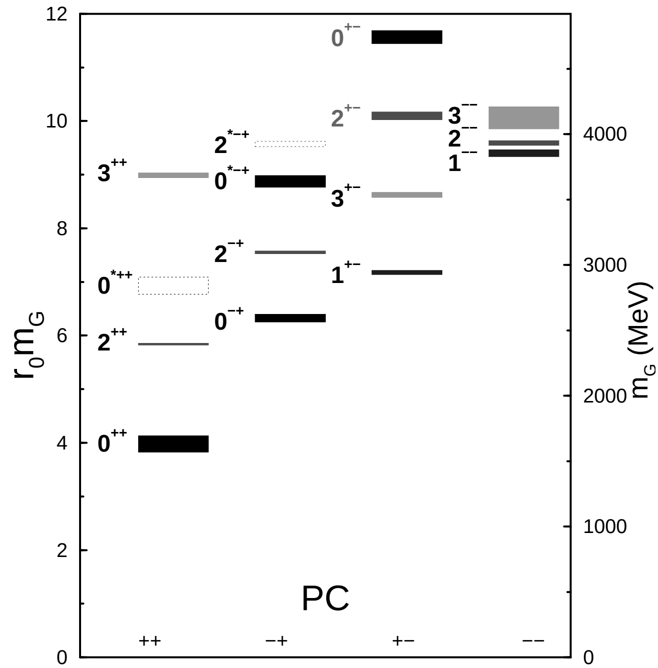

Fig. 3. Lattice-QCD predictions for glueball masses [8]. The states are denoted by their spin (J), parity (P) and charge conjugation (C) quantum numbers.

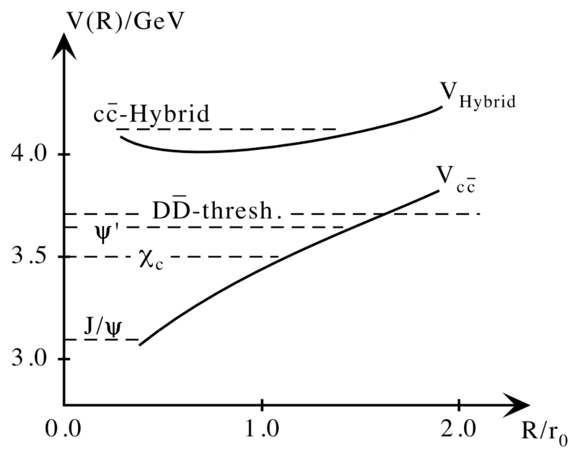

Fig. 4. Potential between static quarks at separation R, in units of $r_0 \approx 0.5$ fm, as derived from Lattice QCD calculations [9]. The V_{Hybrid} potential originates from the first excited state of gluonic flux, giving rise to $c\bar{c}g$ hybrid states.

2.3. In-medium modifications of charmed mesons

The investigation of medium modifications of hadrons embedded in hadronic matter is one of the main research activities at GSI at present and in the near future. The main physics goal is to understand the origin of hadron masses in the context of spontaneous chiral symmetry breaking in QCD and their modification due to chiral dynamics and partial restoration of chiral symmetry in a hadronic environment. Because of the limited energy available, these studies have so far focused on the light quark sector. In particular, the properties of pions [10] and kaons [11] in normal and compressed nuclear matter have been studied.

The proposed experimental program at the HESR will allow an extension of these studies to the charm sector. Recent model calculations [12] predict a lowering of the D^+ and D^- meson masses with a mass split of the order of 50 MeV$/c^2$ (see Fig. 5). A measurable consequence would be a sub-threshold enhancement for D and $\overline{D}$ meson production in $\overline{p}$ annihilation on nuclei [13]. Moreover, a lowering of the $D\overline{D}$ threshold in the nuclear medium by about 100 MeV would allow the Ψ' and χ_{c2} states of charmonium to decay into this channel [14]. Also the width of the $\Psi(3770)$ state which is dominated by the $D\overline{D}$ decay would be affected by a lowering of the D meson mass. A broadening of these states could be detected via lepton pair spectroscopy with the proposed HESR detector system. The HESR would thus offer an optimal framework for exploring the interactions of charmed quarks with nucleons and nuclei. Such investigations are of key importance to the basic understanding of QCD in its non-perturbative regime.

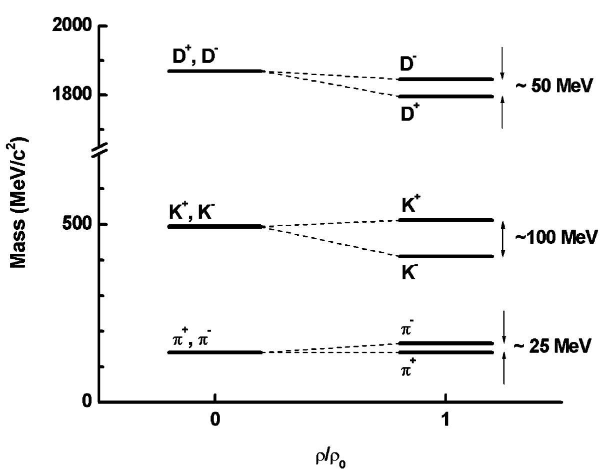

Fig. 5. Schematic plot of free meson masses and mass splitting in the nuclear medium at normal nuclear density. The figure is taken from [1].

2.4. Spectroscopy of Λ and double Λ nuclei

Intense $\overline{p}$ beams will provide a new approach to produce and study hypernuclei, exploiting $\overline{\Xi}^+, \Xi^-$ production near threshold [1, 15]. Hypernuclear physics adds strangeness as a new dimension to the chart of nuclei. Previous investigations were hampered by the limited resolution ($\approx$ 100 keV) of magnetic spectrometers and low statistics. Modern γ-ray detection techniques will allow spectroscopy of hypernuclei with keV resolution. Many of the unanswered questions like the strength of the spin-orbit splitting will become accessible. Of particular importance is the study of double strangeness and even higher strangeness nuclei which are currently either unknown or poorly established. As illustrated in Fig. 6, the pairwise production of hyperons and antihyperons offers the possibility to tag the production process: *e.g.*, a $\overline{\Xi}^+$ with large momentum at forward angles signals the production of a $\Xi^-(dss)$ which, at low momenta, can be captured in a secondary target, forming a $\Lambda\Lambda$ hypernucleus. Combining a high luminosity $\overline{p}$-machine like the

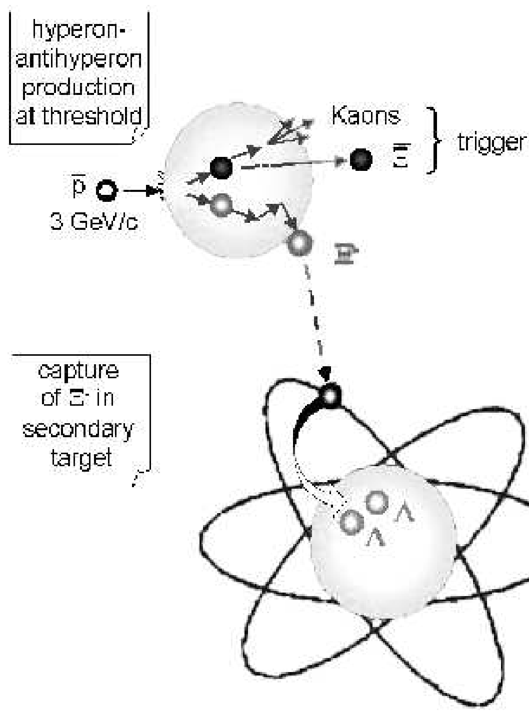

Fig. 6. Schematic illustration of the two-step process for the production of double Λ hypernuclei: a Ξ^- hyperon produced in an antiproton-nucleus collision is stopped in a secondary target and converted into two Λ's. The figure is taken from [1].

HESR with a novel solid-state micro tracker and a large angle Ge-array with high count rate capability, high resolution γ-spectroscopy of double hypernuclei will become possible. These studies will provide direct information on the $\Lambda\Lambda$ interaction, the baryon–antibaryon annihilation dynamics and the interaction of hyperons with nuclei.

3. Why antiprotons?

What are the specific advantages of antiproton beams for the described research program? They are listed in the following:

- $\overline{p}$-beams allow high resolution spectroscopy in formation experiments with resolution limited only by the momentum spread of the beam. The advantage over e^+e^- -colliders, where states with $J^{PC} \neq 1^{--}$ can only be populated in production experiments, is demonstrated in Fig. 7.

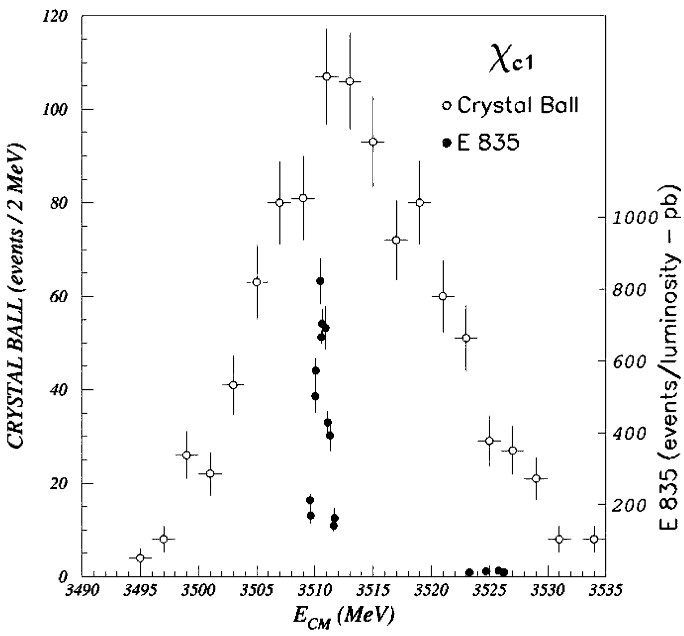

Fig. 7. Mass distribution of the χ_{c1}-state in Charmonium measured in a production experiment at the e^+e^- collider SPEAR with the Crystal Ball detector (open circles) and in a formation experiment with an antiproton beam (full circles) in the E835 experiment at Fermilab. The superior mass distribution achieved in the antiproton experiment is illustrated. The figure has kindly been provided by K. Seth (Evanston).

- Experiments at the Low Energy Antiproton Ring LEAR have demonstrated high production rates for gluonic excitations like glueballs and hybrids comparable to those for mesons [16].
- In $\overline{p}p$ collisions, particles and antiparticles are produced pairwise so that one of them can be used as a tag for the subsequent reaction induced by the other particle. This is particularly important for the formation of double Λ hypernuclei and D-meson physics.
- In $\overline{p}p$ annihilation, massive particles can be produced without much momentum transfer. This is essential for the study of in-medium properties of the produced hadrons which one needs to "implant" in nuclei. A high recoil momentum would kick the produced particles out of the nucleus, making a study of in-medium properties impossible.
- The lifetime of antiproton beams is not limited by decay-in-flight but mainly by consumption in the target. This allows complex beam handling schemes like improving the emittance by stochastic and electron cooling. High quality beams are essential for micro vertex triggers, especially needed for D-meson physics.

Antiprotons are consequently an excellent probe to address the outstanding issues in non-perturbative Quantum Chromodynamics.

4. Storage ring and detector layout

The $\overline{p}$-storage ring and the detector concept are illustrated in Fig. 8. The ring has a circumference of 440 m, two straight sections of 105 m length and a maximum magnetic bending power of 50 Tm. An essential and technically very demanding feature of the High Energy Storage Ring (HESR) is the electron cooler which is required to reach and maintain a luminosity of $L = 2 \times 10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. For the major part of the experimental program a general purpose detector will be used. The detector is almost hermetic with a solenoid around the target and a forward spectrometer. It makes possible the simultaneous detection of neutral and charged particles over the relevant angular and energy range. For this purpose, it will have high granularity, particle identification, high count-rate capability and a sophisticated fast triggering scheme. The inner part of the detector can be modified for the experiments with strange hypernuclei or for the special needs of CP-violation studies. Further details of the HESR and the detector system can be found in [1].

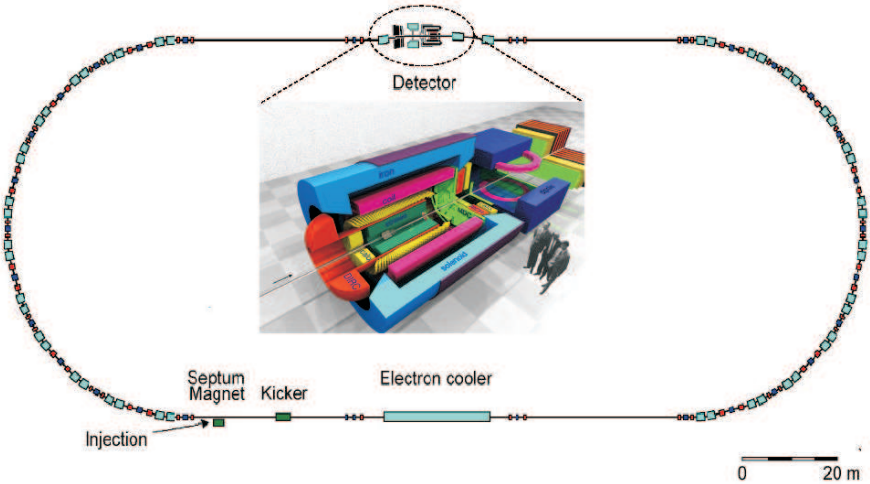

Fig. 8. Layout of the High Energy Storage Ring (HESR). The main features are the electron cooler and the almost hermetic detector system.

5. Conclusions

The interaction of cooled antiproton beams with nucleons and nuclei will provide a broad and challenging hadron physics research program at the HESR, focused on studies of Quantum Chromodynamics in the non-perturbative regime. The high luminosity and monochromaticity of the antiproton beams will provide high precision data and high sensitivity to rare processes. An extension of the research program to tests of fundamental symmetries appears feasible. If realized, the HESR will allow GSI to play a leading role in the exploration of the strong interaction at long distances. The planned investigations at the HESR are complementary to the nuclear reaction and nuclear structure programs proposed for the new facility and will thus be an integral part of GSI's effort to unravel all facets of the strong interaction and of hadronic matter.

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