The Antiproton Project at GSI

Helmut Koch

Institut for Experimental Physics I, Ruhr –Universitaet Bochum,
D-44780 Bochum, Germany

Abstract. Experiments with antiprotons at LEAR and FermiLab have started a new era in hadron spectroscopy. Candidates for bound states with gluonic degrees of freedom were found and the spectroscopy in the charmonium region has reached a new level of precision. It is planned to extend measurements of this kind at GSI/Darmstadt. Antiprotons with energies up to 15 GeV will interact with a Hydrogen cluster target in a storage ring with high luminosity. The machine and the detector will be discussed together with the physics program. The main emphasis will be on the search for missing charmonium states and for charmed hybrids, but the large production rate of $D\overline{D}$ -pairs will also allow searches for rare D-decays and for CP-violation in the charm system.

INTRODUCTION

This talk deals with plans to construct a High Energy Storage Ring (HESR) for Antiprotons at the Gesellschaft für Schwerionenforschung (GSI) at Darmstadt, Germany. The project is part of an upgrade program to the existing facilities and is described in detail in the forthcoming proposal [1]. Antiprotons with momenta between 1.5 and 15 GeV/c will collide with protons (Pellet -or Jet-target) or with heavier nuclei (wire-target) allowing cm-energies as high as 5.5 GeV. The minimal luminosity will be $2*10^{32}$ cm^{-2} s^{-1}, and the relative momentum resolution will be as good as 10^{-4}, for lower energies eventually 10^{-5}, if high energy electron cooling can be realized. The measuring program which is outlined in the following deals mainly with all kinds of non-perturbative QCD-effects with emphasis on the Charm sector.

STATUS OF PHYSICS WITH ANTIPROTONS

High energy antiproton beams have considerably contributed to the recent progress in particle physics. The intermediate Vector Bosons ($w^{\pm}, Z^0$) and the TOP–quark have been discovered using antiproton beams. But also at intermediate energies very successful investigations have been taking place. High precision charmonium spectroscopy experiments were performed at FermiLab [2] and a wealth of interesting data has been obtained at LEAR, particularly in the field of light quark spectroscopy, resulting in the discovery of a good candidate for the glueball ground state [3] and the confirmation of two states with spin-exotic quantum numbers [4,5].

Fig.1 shows a comparison between signals for $\chi_{c_{1,2}}$-states obtained in conventional e^+e^--experiments (Crystal Ball) and in $\bar{p}p$-collisions (E760, FermiLab). In contrast to e^+e^--experiments, $\bar{p}p$- reactions allow the direct formation of these states resulting in a much better mass resolution.

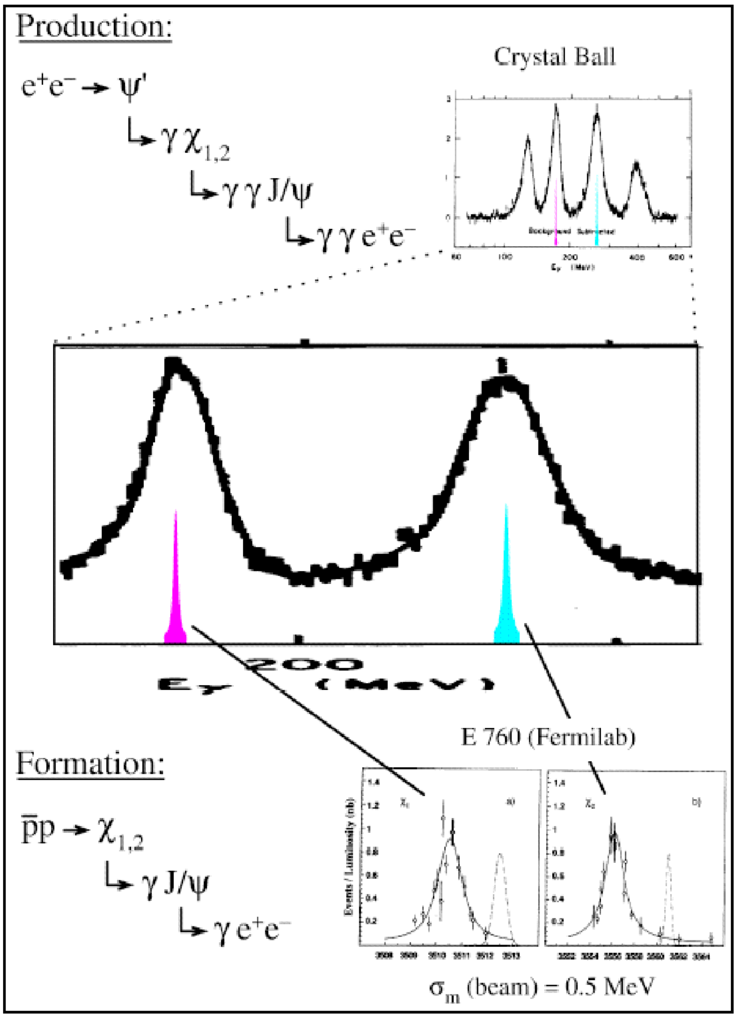

FIGURE 1. Mass spectra for $\chi_{c_{1,2}}$-states as obtained in an e^+e^--production experiment (broad structures) and in a $\bar{p}p$ - formation experiment (narrow structures). This figure was kindly provided by U. Wiedner (Uppsala)

The evidence for a spin exotic state $\pi_1(1400)(J^{PC} = 1^{-+})$ measured with the Crystal Barrel detector at LEAR is shown in Fig. 2. Of particular importance is , that the exotic π_1–state is produced with a strength similar to the one of a conventional $q\bar{q}$-state ($a_2(1320)$). The same is true for the $f_0(1500)$-state, firstly found at LEAR, being at present the best candidate for the glueball ground state.

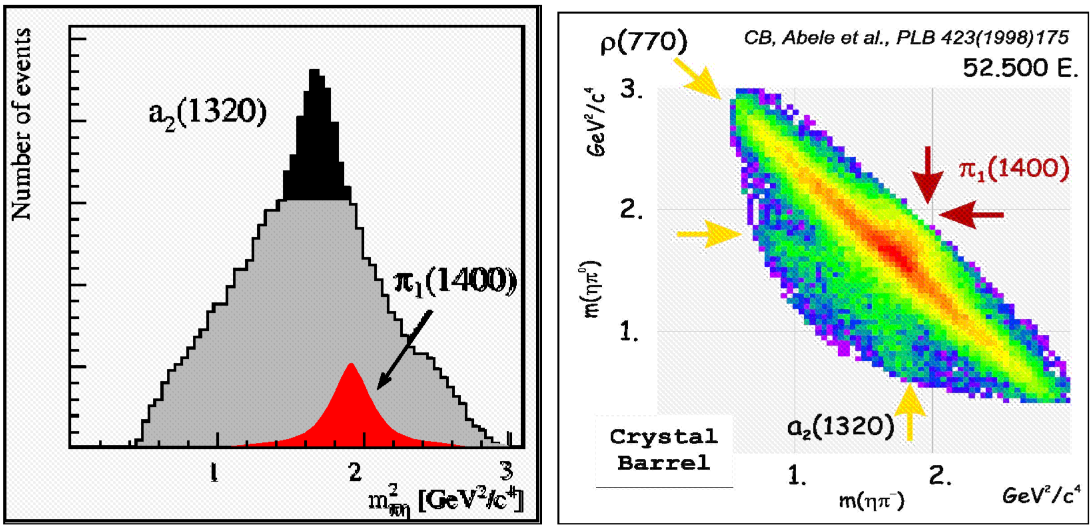

FIGURE 2. Shown on the left is the Dalitz – Plot of the reaction $\bar{p}d \rightarrow \eta\pi^-\pi^o + p$ as measured by the Crystal Barrel Collaboration at LEAR. Shown on the right is the $m^2_{\pi\eta}$ - projection.

Both examples show the merits of experiments with antiprotons at medium energies: (1) The cross sections are high facilitating the search for rare particles. (2) Most particles can be directly created in formation processes regardless of their J^{PC} quantum numbers. (3) Antiproton induced reactions have low particle multiplicities, allowing the reconstruction of complete events and thus reliable partial wave analyses. (4) Exotic states are produced with rates similar to those of $q\bar{q}$ -and qqq–systems. (5) The experimental conditions are very clean due to cooled, high quality $\bar{p}$ - beams.

ANTIPROTON FACILITY AT GSI

Among other projects dealing with Heavy Ion and Plasma physics the upgrade program of GSI foresees a storage ring (HESR) for antiprotons with a maximal energy of 15 GeV. Fig. 3 shows the outline of the assembly: The antiprotons will be produced in the SIS 200 synchrotron allowing the acceleration of protons up to 60 GeV. Up to $2x10^7$ antiprotons per second are produced in a target station very similar to the one at CERN. Accumulation and cooling of the antiprotons is performed in two rings (CR, NESR). Afterwards the antiprotons are injected into the SIS 200 machine in order to accelerate or decelerate them to the desired energy, and they are then ejected into the HESR. The HESR storage ring has two long straight sections for cooling devices and for the set up of a general purpose detector. Using pellet or gas jet targets, luminosities as high as $2x10^{32}$ $cm^{-2}s^{-1}$ can be reached. In a later stage of the project, a luminosity increase to $5x10^{32}$ is envisaged allowing high rate D-pair production on a thin wire target.

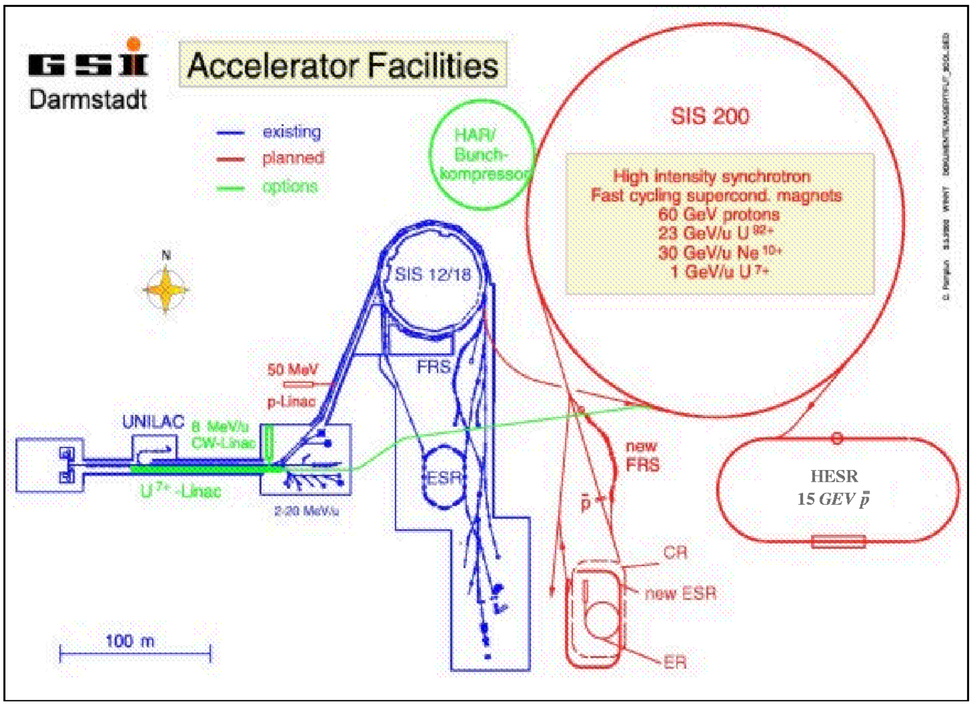

FIGURE 3. Existing and proposed accelerator scenario at GSI [1].

Fig. 4 shows the general purpose detector, which will be used for most of the experiments discussed in the following. It has a nearly full angle coverage for charged particles and gammas, high rate capability and good particle identification (e, μ, π, K, p) and allows efficient triggering on e, μ, K and D's.

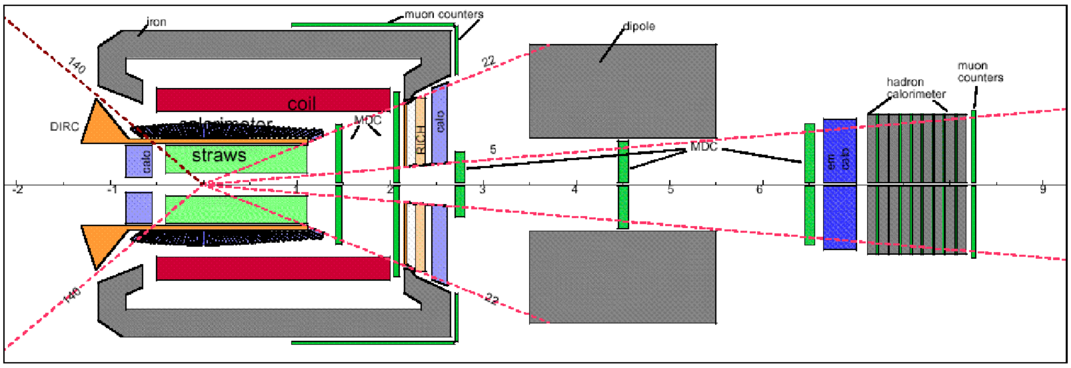

FIGURE 4. General purpose detector for HESR. For special experiments, e.g. the Hypernuclear studies, the area around the interaction point has be modified [1].

The tracking will be performed using a combination of Pixel-, Straw- and Mini-Drift-Chamber detectors. At present an electromagnetic $PbWO_4$ calorimeter with Avalanche-Photodiode readout is foreseen, but also pure CsI is still in discussion. For particle identification Aerogel-Cerenkovs and a Detector for Internally Reflected Cerenkov light (DIRC) will be used. The Muon Chambers consist of Plastic Scintillator strips. The trigger is based on fast Lepton- and Kaon- identification followed by a sophisticated software part using pipeline techniques.

PHYSICS HIGHLIGHTS

The physics program at such a facility is very rich. Besides the topics outlined in the following it also includes low energy experiments, like the study of the $\bar{p}p$-annihilation process, of antiprotonic atoms and high precision experiments on Antihydrogen.

Charmonium Spectroscopy

The latest results of the FermiLab experiment E835 were summarized at this meeting by A. Tomaradze [2]. They are very impressive as far as masses, widths and decay modes of χ_c-states and of the η_c ground state are concerned. However, a lot of problems remains unsolved after the end of data taking at FermiLab. The $^1P_1$-state is not firmly established and the η_c was not seen at all. Most of the D-wave states (some of them may be very narrow) and the radially excited P-states above the $D\bar{D}$-threshold have not been found yet. More exclusive decays have to be studied in order to shed light on anomalies found, e.g. the $\pi\rho$ - puzzle.

The high luminosity of HESR and the universal detector, which - in contrast to the E835 detector - can detect leptonic and hadronic decay modes equally well, will allow to extend the program started at FermiLab considerably. E.g., 10^6 and 10^4 reconstructed J/ψ- and χ_2-states, respectively, are expected per day, allowing scans in the energy regions of interest in steps of 10 MeV, in special cases of 1 MeV. Leptonic modes like e^+e^- and $\mu^+\mu^-$ would be registered in parallel to electromagnetic ($\gamma\gamma$) and hadronic modes ($\phi\phi$,etc.)

Search for Charmed Hybrids

In Fig.5 the occurrence of $c\bar{c}$-Hybrids ($c\bar{c}g$) is demonstrated, originating together with the usual $c\bar{c}$ -states from second order LQCD calculations. Similar results were obtained in various model calculations (Bag, Flux-Tube [6], etc.). All predictions indicate that the lowest energy ($c\bar{c}g$) -states have masses between 3.9 and 4.5 GeV/c^2 with the quantum numbers $J^{PC} = 2^{\mp\pm}, 1^{\mp\pm}, 2^{\mp\pm}, 0^{\pm\mp}$, three of them being spin exotic, including the ground state (1^{-+}). At least several of the states may be narrow (Γ~MeV), as they are forbidden to decay to $D\overline{D}$-pairs. E.g., the 0^{+-} can not decay to $D\overline{D}, \overline{D}^{*}D^{*}, \overline{D}_{s}D_{s}$, due to CP-conservation, and a dynamical selection rule might forbid decays of the kind $(c\overline{c}g) \rightarrow (\overline{Q}q)_{L=0} + (Q\overline{q})_{L=0}$, so that only $(c\overline{c}g)$ states with masses higher than 4.3 GeV/c^2 would decay to $D\overline{D}$. In case that the $D\overline{D}$-mode is forbidden, favorite $(c\overline{c}g)$-decays would contain a J/ψ, e.g. $1^{-+} \rightarrow J/\psi + \omega, \phi, \gamma$.

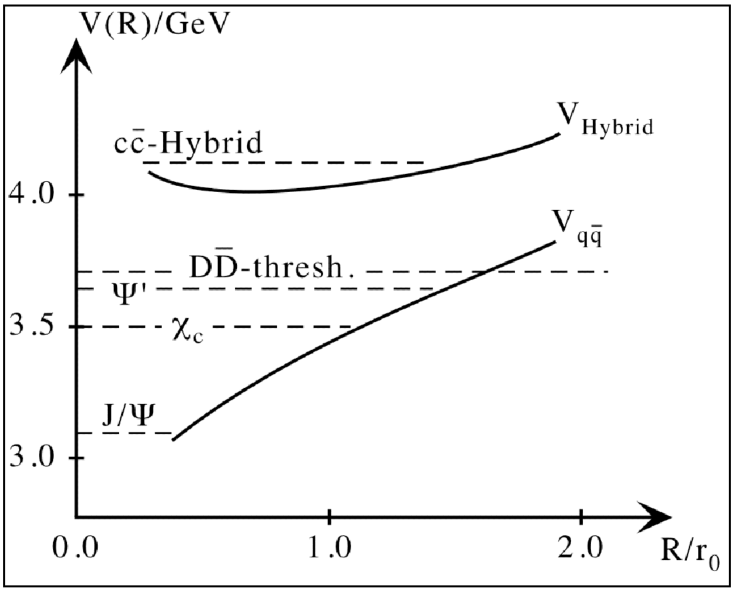

FIGURE 5. $c\overline{c}$ - and $c\overline{c}g$ -potentials resulting from second order LQCD calculations. Also indicated is the position of the usual $c\overline{c}$ -states and of the lowest energy $c\overline{c}$ -hybrid. This Figure was scaled from [7].

The chance to find $(c\overline{c}g)$-hybrids seems to be considerably higher than in the light quark sector due to the lower state density and the narrow widths of states in the charm sector. Non spin exotic states would be searched for in scanning experiments, in parallel to the Charmonium measurements. The rates may be as high as 10^4/day. States with spin exotic quantum numbers have to be detected in production experiments of the type $\overline{p}p \rightarrow (c\overline{c}g) + \pi^{0}/\eta$. Here, the rates are lower (10^2/day), but still sufficient for a spin-parity analysis.

In addition, of course, a program for measurements of hybrids in the light quark sector concentrating on the mass region around 1.9 GeV/c^2 can be easily performed.

Search for Heavier Glueballs

LQCD predictions for the glueball mass spectrum are shown in Fig. 6. The spectrum extends up to 5 GeV/c^2, also exhibiting several spin exotic glueballs (odd balls), the lightest one ($J^{PC} = 2^{-+}$) at 4.3 GeV/c^2. Again, at least in special cases, e.g. for odd balls, the widths may be reasonably narrow. The search for such states would proceed in parallel to the measurements discussed before. Favorable decay channels would be $\phi\phi$ or $\phi\eta$, which are easily distinguishable from typical annihilation reactions and exhibit low *l*-waves facilitating a spin parity-analysis.

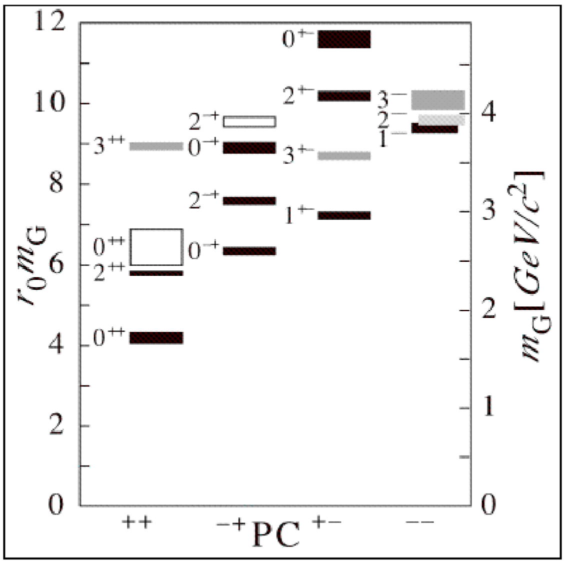

FIGURE 6. Glueball mass spectrum as predicted by LQCD [8].

Experiments with open Charm/ Strangeness

The production rate for reconstructed $D\overline{D}$ pairs (up to 10^7/year) at HESR is comparable to the one of a τ/c-factory. Also charmed and strange Baryon-Antibaryon pairs are produced with high rates, e.g. 10^7 $\Lambda_c\overline{\Lambda}_c$ and 10^9 Ξ^- Ξ^+ per year. The experimental conditions for spectroscopy experiments are very favorable, as all pairs will be produced near threshold, resulting in modest particle energies and low multiplicity events. One of the particles can be used for trigger purposes allowing a complete investigation of its partner.

The experimental program incorporates Baryon spectroscopy experiments and the investigation of rare D-decays. An example would be leptonic D-decays ($D^+ \to \mu^+\nu$), the rate of which is predicted by LQCD and is a sensitive test of the D-structure.

In a later stage also CP-violation experiments are feasible [9]. The comparison of the angular decay asymmetries for $\Lambda \to p\pi^-$ and $\overline{\Lambda} \to \overline{p}\pi^+$ is a sensitive test of direct CP-violation in the Baryon sector [10]. Also CP-violation in the $D^0\overline{D}^0$ - sector can be investigated. According to the Standard Model CP-violation in mixing is very small [11], but direct CP- violation could be searched for in single Cabibbo suppressed decays.

Antiproton Nucleus Interactions

In recent experiments at GSI it was found that charged Pions [12] and Kaons [13] exhibit effective masses, different from their vacuum values, when these particles are produced in a nuclear medium (see Fig.7). The effects are due to the quark condensate. Similar effects are predicted for D^+ and D^- [14], which, however, depend on the gluon condensate, leading to a decrease of D^-/D^+ - masses in nuclear matter. This would produce very spectacular effects, when ($c\bar{c}$)-states are produced via $\bar{p}p$ - annihilation in nuclear matter. The $D\bar{D}$ - threshold would be lower than its vacuum value leading to a substantial increase of the width of the ψ''- state. e.g.

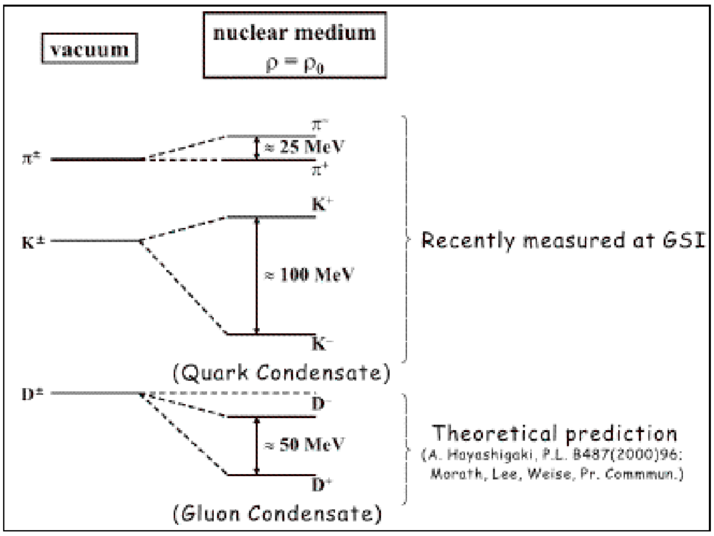

FIGURE 7. Experimental values and predictions for effective masses of Pions, Kaons and D-Mesons inside a nuclear medium.

For the identification of the Quark-Gluon-Plasma the magnitude of the J/ψ- Nucleon absorptive cross section plays a decisive role. It could be measured with high accuracy in a $\bar{p}$-scan between 3.4 and 4.6 GeV/c, observing the reaction $\bar{p} + A \rightarrow J/\psi + (A-1)$. Similar experiments could be performed on other ($c\bar{c}$)-states.

The investigation of Hypernuclei adds a third dimension to the nuclear chart yielding very valuable information on nuclear structure. Of particular interest are double Λ-Hypernuclei, for which only three candidates exist yet. They can be copiously produced at HESR using the two-step reaction

$$\bar{p}\,(2.6\ \mathrm{GeV/c}) + \mathrm{A} \rightarrow \Xi^-_{slow} + \bar{\Xi}^- Trigger\,;\ \Xi^-_{slow} + A' \rightarrow {}_{\Lambda\Lambda} A'$$

As a secondary active target (A') high resolution solid state micro-tracking detectors (Diamond, Si) are used together with an efficient, position sensitive Ge-γ-array [15,16] allowing high rate spectrocsopy experiments yielding hundreds of γ-transitions per-day. For these experiments the interior of the general purpose detector has to be modified accordingly

STATUS OF THE PROJECT

The parameters of the SIS 200 synchrotron and of the HESR are worked out in detail. The performance of the general purpose detector was studied using a sophisticated Geant 4 simulation and was found to match the expectations [17]. The proposal for the GSI upgrade will be available soon [1]. Referee Committees have started with the survey of the project and a decision is expected in the middle of the year 2002.

CONCLUSIONS

Antiproton induced reactions which can be studied at the High Energy Storage Ring at GSI exhibit unique features: (1) Gluonic hadrons seem to have high production rates in $\bar{p}p$- annihilation. (2) High statistics data with low multiplicity events with a symmetric production of particles and antiparticles will be obtained. (3) Many of the interesting states can be directly formed and investigated in a scan-mode with high mass resolution. A rich and unique Physics Program with emphasis on charmed particles can be performed including J/ψ-nucleon interactions, the study of effective hadron masses in nuclear matter, precision charmonium spectroscopy and the search for charmed hybrids and heavier glueballs. In a later stage, even CP-violation experiments are in reach. Additionally, the low energy experiments started at LEAR could be continued, also including further studies on Antihydrogen.

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