THE PHYSICS PERSPECTIVES AT THE FUTURE ACCELERATOR FACILITY FAIR

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Abstract

The future international accelerator Facility for Antiproton and Ion Research FAIR at Darmstadt, Germany will serve as research facility for a large community of scientists in Europe and around the world. It will expand on experiences made at GSI in combining synchrotrons with storage rings, and will open access to a broad spectrum of experimental approaches. The physics of strongly interacting systems is the main research field, but also aspects of atomic and plasma physics as well as material science will be addressed. The key features of the facility are high intensities, multi-user parallel operation and brilliant beams of secondary reaction products, i.e. exotic instable nuclei and anti-protons. The opportunities have attracted by now three large communities interested in nuclear structure studies using rare isotopes, hadron spectroscopy exploiting collisions of anti-protons with various targets and physics of ultra-dense nuclear matter created in central collisions of very heavy ions. Moreover, many smaller groups of scientists have proposed exiting experiments to investigate e.g. anti-matter, QED in strong fields and strongly correlated plasmas.

INTRODUCTION

At the end of the past decade the Gesellschaft für Schwerionenforschung (GSI), together with Universities and various international user groups, triggered an initiative aimed at providing the European and international science community with a new, world-wide unique accelerator complex. The Conceptual Design Report [1] was presented to the German Ministry for Education and Research in 2002 and was finally approved in 2003 after evaluation by an International Expert Committee put in charge by the German Science Council. The projected facility has been optimized to guarantee excellent conditions for future challenging experiments on open questions concerning - in broadest terms - many-body system governed by the strong interaction and also in related fields. The concept of the future facility founds on the positive experiences made at GSI with combining a synchrotron and a storage ring. Its layout is depicted in Fig. 1.

About 100 years after Rutherford's discovery of the atomic nucleus compelling information about the structure and reaction of nuclei has been collected. As of this, nuclear physics nowadays is concerned with a much broader scope of questions ranging from the dynamics of the elementary quarks and gluons to the evolution of super-nova explosions and the formation of neutron stars. Objects, which differ in size by almost 20 orders of magnitude,

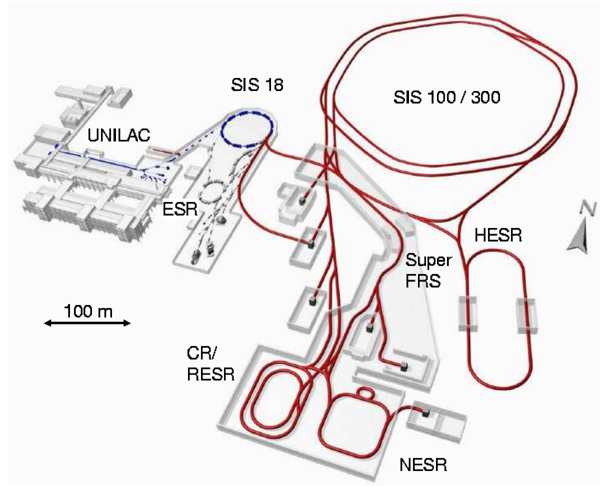

Figure 1: Projected layout of FAIR. The future facility (plotted in red) will be arranged around the old GSI accelerator complex (plotted in blue) comprising the Universal Linear Accelerator UNILAC, a 18 Tm synchrotron (SIS 18) and the Experimental Storage Ring (ESR). The new complex is composed of a rapid cycling 100 Tm synchrotron SIS 100 and a stretcher synchrotron SIS 300 for maximum beam energy and slow extraction. The new super fragment separator (Super FRS) will catch secondary reaction products after dissociation of stable beams of highest intensities. A set of three storage rings is used for collection and pre-cooling (CR), deceleration (RESR) and in-ring experiments with secondary beams in the New Experimental Storage Ring (NESR). The large high energy storage ring (HESR) will provide circulating brilliant beams of antiprotons.

but all essentially governed by the strong interaction. Recently, various national and international advisory committees have outlined the most important avenues for nuclear research in the next decade [2, 3, 4]. Among the top priority research direction are:

- Properties of hot and dense nuclear matter and new phases of matter.
- Non-perturbative effects of QCD and the formation of hadrons.
- Structure and reactions of short-lived, exotic isotopes.
- Symmetries and physics beyond the standard model.

Besides their importance in their own, these fields are intimately linked to the microscopic understanding of cosmological and astrophysical processes.

Although the larger part of the user community will work in nuclear and hadron physics, a still growing fraction of

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the user community plans to exploit the possibilities of using ion and antiproton beams for probing the electromagnetic interaction in ultra-high fields and in systems built from anti-matter. In the next section the physics program of five mayor research activities will be outlined. The operating principle of the facility is presented in the subsequent section. The paper concludes with a short summary.

THE PHYSICS PROGRAM OF FAIR

Compressed Baryonic Matter

Nuclear matter accounts for more than 99 % of the mass of all directly observable matter around us. To most extend it occurs in the interior of atoms where it forms the nucleus. Filling only one trillionth of the volume of the atom it accounts for about all of the its mass. Independent of the size of the nucleus, its constituents, the nucleons, gather at a saturation density of 0.17 nucleons/fm^3 thus achieving a bulk mass density of 280 Million tons per cm^3. Yet nature provides much larger samples of nuclear matter with a few kilometers diameter, and core densities which outreach nuclear saturation density by factors: the neutron stars.

The exploration of the different phases of nuclear matter as temperature and density increases is the core subject of heavy ion reaction experiments at relativistic and ultra-relativistic energies. Once nuclear matter is heated, it converts from a liquid phase into a gas of hadrons. At yet higher temperatures the hadron gas again undergoes a phase transition into a gas of de-confined quarks and gluons. Collisions of heavy nuclei is the only tool to control the state variables of nuclear matter in the laboratory. The current knowledge is summarized in Fig. 2. In the past twenty years the phase diagram was mapped by analyzing the chemical composition of the reaction products of the decaying hot interaction volume. Meanwhile there are many indications that a de-confined state is reached at beam energies above 100 AGeV, or even somewhat below. This conjecture is evidenced by recent lattice QCD calculation which derive a phase boundary located at about 170 MeV temperature at small (net) baryon densities, exactly at the maximum freeze-out temperatures extracted from experiment.

The physics goal of the Compressed Matter Experiment CBM at FAIR is to map the phase diagram in the region of high baryon density (shown as hatched area in Fig. 2). In this region of the phase diagram the location of the phase boundary is much more uncertain. Moreover, at very high densities new exotic phases of nuclear matter are expected, like e.g. a color super-conducting phase. According to lattice calculations nuclear matter should also feature a critical point in the region accessible by the future accelerator. To identify this point experimentally would be a clear prove for the existence of a phase transition into the de-confined phase. CBM is designed to observe both, the bulk hadronic particles produced in the violent collisions but also products of rare decays out of the early phase of the collision zone. In order to be sensitive to such decays the spectrometer has to cope with high count rates and large integral luminosities. This experiment will typically use beam from the stretcher synchrotron SIS 300 in the slow-extraction mode and and will take data for different energies up to the highest possible (i.e. $\approx 35 A$GeV for ^{238}U).

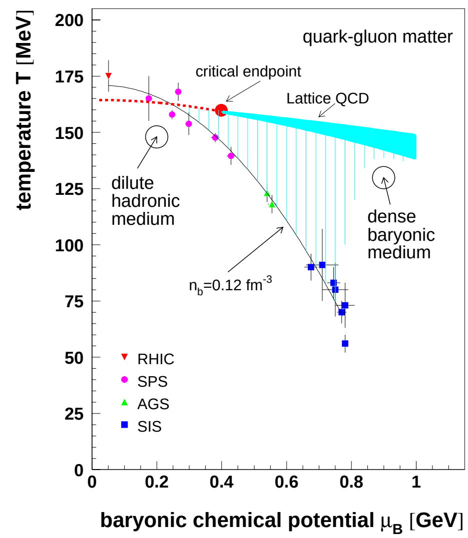

Figure 2: Location in the nuclear matter phase diagram of freeze-out configurations reached after collisions of heavy ions at center-of-mass energies per nucleon ranging from 2 - 200 GeV. The ordinate represent the temperature and the abscissae the baryonic chemical potential at the instant in time during the evolution of the nuclear fireball, when inelastic collisions between the constituents cease. The data points are derived from statistical model description of the hadronic final state recorded by the detectors. Their location can be described by a universal freeze-out condition defined by constant baryon number density n_b.

Research with Antiprotons

Although originally considered elementary particles, nowadays nucleons appear as rather complex realizations of QCD. Substantial research has been conducted over almost 50 years and many details have been unravelled. Yet a comprehensive theoretical description of nucleons, or more general hadrons, is not available. QCD is simple and well understood at short-distance scales, much shorter than the size of a nucleon ($\ll 10^{-15}$ m). In this regime, the basic quark-gluon interaction is sufficiently weak and one can apply perturbation theory. The perturbative approach, however, fails completely when the distance among quarks becomes comparable to the size of the nucleon. Under these conditions, the force among the quarks becomes so strong that they cannot be further separated, in contrast to the electromagnetic and gravitational forces, which fall off with increasing distance. This is the reason why freely propagating quarks have never been observed and why a tremendous energy density is necessary to create deconfined matter in heavy ion collisions.

The only known QCD objects are baryons and mesons, which are composed of three quarks and a quark anti-quark

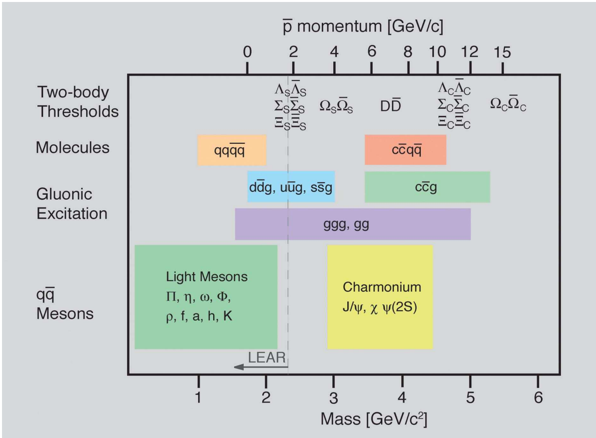

Figure 3: Mass range of hadrons accessible at the HESR with antiproton beams. The figure indicates the antiproton momenta required for charmonium spectroscopy, the search for charmed hybrids and glueballs, the production of D meson pairs and the production of Î baryon pairs for hypernuclear studies. The energy range covered by the former Low Energy Antiproton Ring (LEAR) at CERN is indicated by the arrow.

pair, respectively. QCD, however, also predicts objects composed entirely by gluons (glueballs) and mixtures of quarks, anti-quarks and gluons, so-called hybrids. To discover such states would mark an important milestone in the detailed understanding of the nature of matter. Another striking feature of non-perturbative QCD is the fact that the elementary light quarks, the up and down quarks, making up the nucleon have very small masses which amount to only a few percent of the total mass of the nucleon. Most of the nucleon mass, and therefore of the visible universe comes from the QCD interaction. This generation of mass is associated with the confinement of quarks and the spontaneous breaking of chiral symmetry, one of the fundamental symmetries of QCD in the limit of massless quarks. These phenomena, the confinement of quarks, the existence of glueballs and hybrids, and the origin of the mass of strongly interacting, composite systems related to confinement and the breaking of chiral symmetry are long-standing puzzles.

At the future facility, intense beams of cooled antiprotons will be used to address the issues presented above. Antiproton beams at momenta between 1 and 15 AGeV/c on fixed target will provide access to the heavier strange and charm quarks and to copious production of gluons, as is illustrated in Fig. 3. A dedicated high acceptance and high rate spectrometer $\bar{\text{P}}$ANDA [5] is currently developed to cope with the high luminosities achievable in an HESR in-ring experiment. $\bar{\text{P}}$ANDA aims at rates equivalent to 10 pb^{-1}/day. Cooled antiproton beams are ideally suited for spectroscopic experiments in the charm region. In formation experiments, the precision achievable in the determination of masses and widths of all charmonium states depends only on the quality of the antiproton beam and target, and not on any detector properties. Antiproton beams can be cooled (stochastic and/or electron cooling) to obtain a relative momentum resolution of better 10^{-5}. Thus, the beam energy resolution can be translated directly to mass resolution if very thin targets of hydrogen gas jet or hydrogen pellets are used in the stored circulating beam of antiprotons.

The Structure of Exotic Isotope

QCD explains the strong interaction by exchange of gluons. Compared to QED the strong force develops a rich structure as the gluons itself are carriers of the (color) charge. Already the interaction between nucleons has the character of a residual interaction, commonly described by exchange of virtual mesons. In nuclei the dynamics of the nucleons is essentially defined by three interactions: the strong, electromagnetic and weak forces. The first two interactions control the isotopic character of nuclei by balancing attraction and repulsion. The weak force transmutes unstable atomic nuclei into others and ultimately into stable nuclei. QCD, however, does not deliver a precise analytical form of the strong interaction at a length and energy scale relevant to nucleon-nucleon interactions in nuclei. To determine the emerging effective strong interaction represents a fundamental goal of nuclear physics. Probing nuclei under extreme conditions in various respects paves the way towards a more comprehensive understanding of nuclear matter.

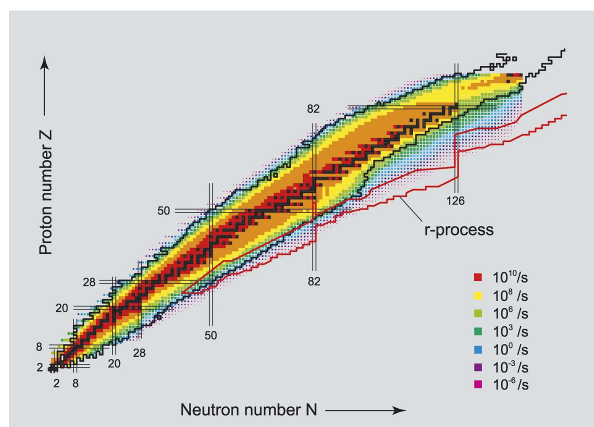

Figure 4: Expected production rates for unstable isotopes after fragmentation of primary stable beams at the FAIR facility. The production rates are indicated by a color code shown bottom right. Stable isotopes are printed in black. As yet unexplored parts of the presumed r-process path (hatched area) will become accessible, in particular around the closed neutron shells N=82, N=126 and even beyond.

All atomic nuclei in the universe beyond lithium have been and still are being created in stars. In various stellar environments this nucleosynthesis proceeds via the formation of transient nuclei that decay into stable ones, either directly or after several intermediate steps. A precise knowledge of the structure and reaction of exotic nuclei, far off from the valley of stability is an essential ingredient to astrophysical model calculation simulating the evolution of explosive stellar processes.

Nuclei can also serve as test grounds for fundamental symmetries. Low-energy experiments addressing fundamental symmetries and their possible violations have been performed for a long time. Such studies comprise accurate tests of parity and time-reversal symmetry.

The new facility will open a qualitatively and quantitatively new era, since the considerably increased production yields for exotic nuclei together with novel beam manipulation techniques, such as beam cooling, deceleration to rest and storage in ion or atom traps, will increase the precision achievable in these studies by one order of magnitude and more. FAIR will provide primary beams of stable isotopes at intensities that are a factor of 100 higher than presently available at GSI. Secondary radioactive beam intensities will even increase by a factor of up to 10,000 through advanced concepts for beam separation and secondary beam phase-space handling. The maximum beam energies of the radioactive species will be unparalleled by any other existing or planned facility. Altogether, this will allow sensitive experiments with secondary beam species far away from stability (see Fig. 4). A large unser community (NUSTAR) [6] has proposed experiments using high energy reactions on fixed targets, in-beam scattering on internal targets as well as on colliding electron beams, decay spectroscopy at small energies or with stopped isotopes and finally ions stored in the NESR or in traps.

Atomic Physics in Strong Fields

FAIR has key features that offer a range of new opportunities in atomic physics and related fields. First, high charge-state ions, moving at velocities close to the speed of light, generate electric and magnetic fields of exceptional strength. Second, at those relativistic velocities, the energies of optical transitions, such as those of lasers, are boosted to the X-ray region. The strong fields carried by heavy, highly-charged ions are their outstanding attributes for atomic and applied physics research.

For the heaviest ions, Quantum Electrodynamics (QED), the Standard Model of electromagnetism and a basis of modern physics, will be probed near the critical field limit associated with the extreme conditions of high charge states and high velocities. The fields present in highly relativistic collisions are strong enough to produce real e+e- pairs directly out of the vacuum. Precision studies of QED in bound states will become possible through the large Doppler shifts of highly relativistic ions, which generate extreme energy shifts for photons in the ion rest frame. As a consequence, even the heaviest few-electron ions can now be studied in precision QED experiments by using state of the art laser systems.

By means of collinear laser spectroscopy the ground state hyperfine-splitting of very heavy, hydrogen-like atoms has been probed with high accuracy. Based on this experience, nuclear properties like radii, spins, magnetic dipole moments and higher electromagnetic moments of nuclei very far off stability will be addressed at the new facility by experimental techniques of atomic physics. Many of the research topics mentioned from collision studies to spectroscopy that were started successfully at the ESR, will be expanded into new regimes under much better and advanced experimental conditions at the NESR.

The Physics of Strongly Coupled Plasmas

A particularly interesting plasma region, the dense, strongly coupled plasma, is located at relatively low temperature and high density. The interior of the giant planets Saturn or Jupiter are interesting examples for this dense plasma region. The investigation of the properties of dense plasmas is at the focus of plasma physics research with the new facility. Of particular interest is the occurrence of phase transitions in cold compressed material, e.g. the insulator-to-metal transition of diamond expected at 10 Mbar, the insulator-to-metal transition of solid hydrogen predicted above 5 Mbar, or the plasma phase transitions at temperatures of about 1 eV. With the presently available beam pulses from the SIS18, a specific power deposition up to 50 GW/g is achieved resulting in a pressure inside the investigated solid-state target of only some 10 kbar.

The SIS 100 heavy-ion synchrotron combined with a bunch compression system for the generation of very intense short ion bunches below 50 ns pulse length will extend the available beam deposition power from the current level of 50 GW/g by more than two orders of magnitude up to 12,000 GW/g. This will open up unprecedented opportunities for the production of ion beam heated and/or compressed plasmas.

RUNNING IN PARALLEL

The different research programs outlined before require various running conditions. Plasma physics, i.e. is interested in receiving ultra short beam pulses at repetition rates in the order of minutes or longer. The high-energy antiproton program runs with one fill of the HESR for up to an hour. Such long repetition times are achieved by continuously cooling the beam to accommodate for the energy dissipation in the target. A major design criteria for the FAIR accelerator complex was the optimum use of the facility by allowing parallel operation of dedicated physics runs. In Fig. 5 we outline the scenario for three different experiments.

In the uppermost panel beam is produced for CBM. A preferably heavy beam is accelerated in three steps up to the maximum energy possible. After achieving maximum rigidity in SIS 300, the beam is slowly extracted onto the target station of the CBM spectrometer. During this extraction time - the goal is to achieve several tens of seconds - all facilities except SIS 300 are available to accelerate a different beam.

This time can be used e.g. for rare isotope studies using storage rings (middle panel). Primary beams are acceler-

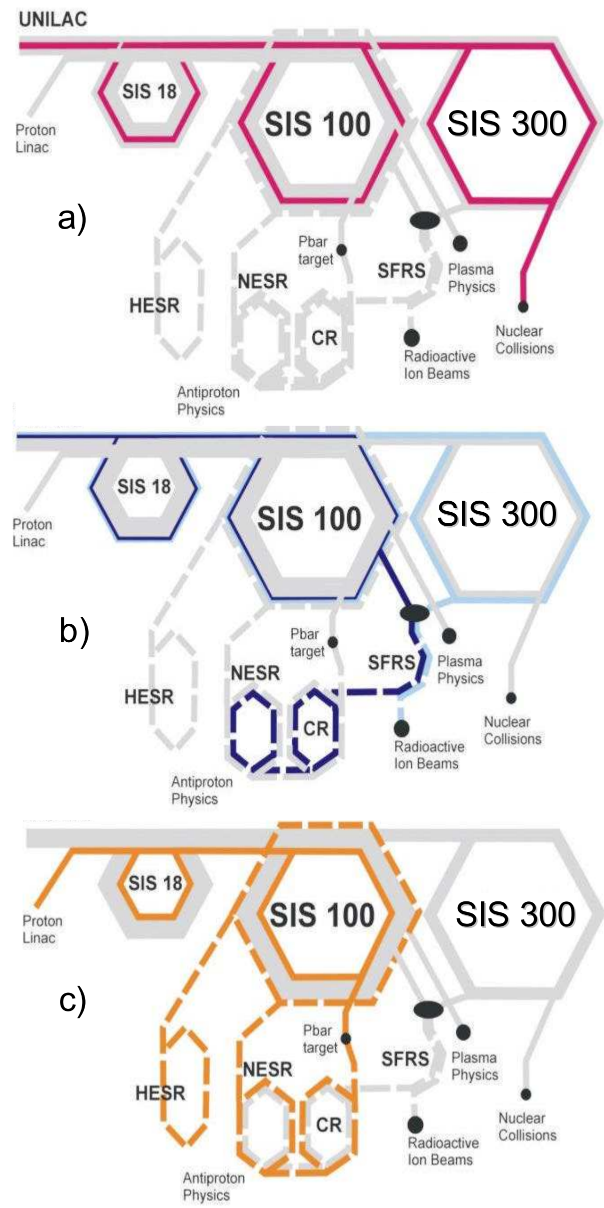

Figure 5: Pictorial representation of the beam transport through the elements of the facility for three different experimental runs. Case a) shows the acceleration of heavy ion the the highest beam energies as needed e.g. for the CBM experiment. Case b) depicts the production of rare isotopes which are cooled, decelerated and stored in the NESR. Case c) finally illustrates the production, cooling, re-acceleration and storage of antiprotons. For a detailed description see the text.

ated in SIS 100 up to typically 1 AGeV beam energy. The comparably high rigidity of the synchrotron is needed to accelerate low charge states, a measure to extend the space charge limit. Fast extraction is used to feed the secondary particle beam into the collector ring. After cooling and deceleration the beam is finally directed to the NESR. In case fixed target experiments are conducted, the beam is directed from SIS 100 to SIS 300 and slowly extracted into the respective target stations. In this case, the CBM experiment can not run in parallel.

An operational mode using most of the facility at once is shown in the lower panel. This mode is for production of antiproton beams. A primary proton beam is accelerated to 30 GeV/c momentum and directed on the antiproton production target. The antiprotons, which feature a wide momentum spread, are collected in the CR and pre-cooled in the NESR. After having collected sufficient antiprotons the particle beam is re-injected into the SIS 100, accelerated to the required energy and directed to the HESR.

SUMMARY

The future international accelerator facility FAIR will provide ideal conditions for next generation experiments dedicated to the exploration of strongly interacting (many-body) systems. It will establish a world-wide unique laboratory providing ion beams and antiprotons for experiments attracting also neighboring research communities. The expected user community comprises currently more than 1400 researchers. To achieve this goal advanced technologies have to be developed for high performance super conducting magnets and high energy beam cooling. The total project time until commissioning amounts to about 8 years. Part of the experimental program can begin at earlier times due to a sophisticated, staged construction schedule.

ACKNOWLEDGEMENT

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