Future Facility: FAIR at GSI

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The Facility for Antiproton and Ion Research, FAIR, is a new particle accelerator facility to be built at the GSI site in Germany. The research at FAIR will cover a wide range of topics in nuclear and hadron physics, high density plasma and atomic physics, and applications in condensed matter physics and biology. A 1.1 km circumference double ring of rapidly cycling 100 and 300 Tm synchrotrons, will be FAIR's central accelerator system. It will be used to produce, *inter alia*, high intensity secondary beams of antiprotons and short-lived radioactive nuclei. A subsequent suite of cooler and storage rings will deliver heavy ion and antiproton beams of unprecedented quality. Large experiments are presently being designed by the NUSTAR, PANDA, PAX, CBM, SPARC, FLAIR, HEDgeHOB and BIOMAT collaborations.

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1. INTRODUCTION

FAIR will provide the scientific community with a world-wide unique and technically innovative particle accelerator system to perform cutting edge research in the sciences concerned with the basic structure of matter (cf. Ref. [1–3]). The facility will provide an extensive range of beams from protons and antiprotons to ions up to uranium with world record intensities and excellent beam quality in the longitudinal as well as transverse phase space. The scientific goals pursued at FAIR include:

- Studies with beams of short-lived radioactive nuclei, aimed at revealing the properties of exotic nuclei, understanding the nuclear properties that determine what happens in explosive processes in stars and how the elements are created, and testing fundamental symmetries.
- The study of hadronic matter at the sub-nuclear level with beams of anti-protons,

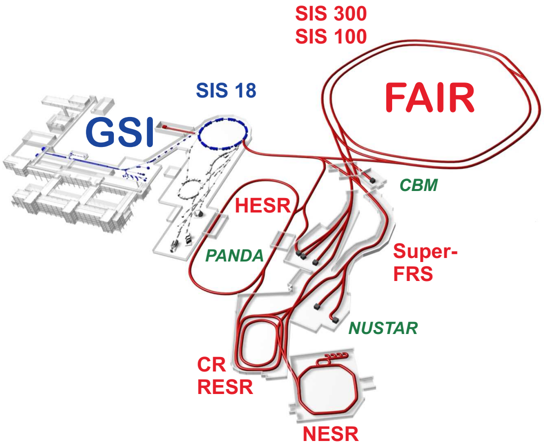

Figure 1. FAIR at GSI: SIS 18, 100, 300 = synchrotrons with bending powers of 18, 100 and 300 Tm, respectively; CR = Collector Ring; RESR = Accumulator Ring; NESR & HESR = low & high energy experimental storage rings, Super-FRS = Fragment Separator.

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in particular of the following key aspects: the confinement of quarks in hadrons, the generation of hadron masses by spontaneous breaking of chiral symmetry, the origin of the spins of nucleons, and the search for exotic hadrons such as charmed hybrid mesons and glueballs.

- The study of compressed, dense hadronic matter through nucleus-nucleus collisions at high energies.
- The study of bulk matter in the high density plasma state, a state of matter of interest for inertial confinement fusion and for various astrophysical sites.
- Studies of Quantum electrodynamics (QED), of extremely strong electromagnetic field effects and ion-matter interactions.

2. ACCELERATORS

The central part of the FAIR facility consists of the SIS 100 and SIS 300 accelerators, two up to 4 T/s rapidly cycling synchrotrons along a perimeter of 1100 m and with maximum magnetic rigidities of 100 and 300 Tm, respectively (cf. Fig. 1). Heavy ion (HI) beams will be injected from the existing GSI UNILAC and SIS 18 accelerators, high intensity proton beams, as needed for antiproton production, from a new linear accelerator in front of the SIS 18. Both HI and proton beams will be compressed to very short bunch lengths for the production of exotic nuclei (60 ns) or antiprotons (25 ns).

Continuous beams with intensities up to $3 \cdot 10^{11}$ ions/s will be provided at energies of 1 GeV/u either directly from the SIS 100 or by transfer to, and slow extraction from, the 300 Tm ring. The SIS 300 will deliver HI beams of maximum energies around 45 GeV/u for Ne^{10+} beams and close to 35 GeV/u for fully stripped U^{92+} beams. The maximum intensities in this mode will be close to $1.5 \cdot 10^{10}$ ions per spill.

The accelerators will be complemented by a number of cooler and storage rings run in parallel operation:

- The Collector Ring (CR) for stochastic cooling of antiproton or radioactive ion beams. In addition, this ring offers the possibility of measuring the masses of short-lived nuclei by operating it in isochronous mode.
- The Accumulator Ring (RESR) for the accumulation of antiprotons and for the fast deceleration of short-lived nuclei.
- The New Experimental Storage Ring (NESR) for various experiments with ion or antiprotons beams. Equipped with stochastic and electron cooling devices it will house a variety of experimental devices including a precision mass spectrometer, internal target set-ups for experiments with atoms and electrons and an electron-nucleus collider. The NESR will be capable of further decelerating ions and antiprotons and extracting them for use in the antimatter FLAIR experiments.
- The 50 Tm High Energy Storage Ring (HESR) is optimised for acceleration and storage of antiprotons of energies up to 14 GeV. The ring will operate with an internal target and associated detector set-up (PANDA experiment). It will be equipped with a stochastic cooling system and a 5 MV electron cooler to compensate for beam degradation due to target interaction and intra-beam scattering.

3. COLLABORATIONS

The physics programme at FAIR addresses three main areas of research: Nuclear and Astrophysics with radioactive beams (NUSTAR Collaboration), strong QCD physics with (polarised) antiprotons (PANDA and PAX Collaborations) and high-energy HI beams (CBM Collaboration), and applications of HI and antiproton beams (SPARC, FLAIR, HEDgeHOB and BIOMAT Collaborations). Only NUSTAR, PANDA and CBM will briefly be described below.

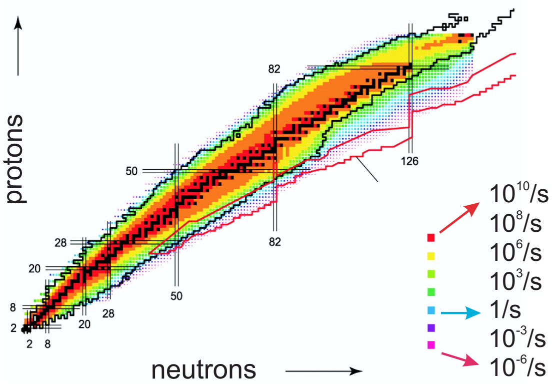

Figure 2. Production rates of radioactive nuclei at the Super-FRS. The r-process in supernovae explosions is believed to proceed within the zone outlined in red on the right hand side of the figure.

3.1. NUSTAR

The NUSTAR Collaboration will study nuclei at the limits of their existence (cf. Ref. [4]). The central facility of NUSTAR is the Super Fragment Separator, which will analyse very short-lived radioactive nuclei at intensities as shown in Fig. 2. As one moves away from stability on the neutron-rich side one approaches a region where the proton/neutron ratio is drastically different from that in stable nuclei. Here, the isospin dependence of nuclear structure phenomena can be studied and weaker binding is expected to bring about extended surface zones of neutron-enriched, low density matter. The study of these neutron skins or halos determines the effective interactions in such nuclear environments and thus will help to investigate the equation-of-state of cold neutron matter between saturation and low density. Investigations of the most neutron-rich isotopes also offer direct access to part of the astrophysical r-process path, leading to a fruitful synergy of nuclear structure and nuclear astrophysics. The location of the nucleon drip-lines is determined by a whole range of effects; the Coulomb force, changing shell structure, nucleon-nucleon correlations and proton-neutron asymmetry, amongst other things. The proton drip-line lies quite close to stability because of the effects of the Coulomb force and we have already mapped it out roughly. The beams from FAIR will allow us to produce the nuclei at the proton drip-line in abundance and allow us to study them in detail. More interestingly, the neutron drip-line is thought to lie a long way from stability in the heavy elements because there is no Coulomb repulsion between neutrons. It is known only for light elements up to oxygen ($Z = 8$) and it will be very difficult to reach beyond $Z = 25$. For heavy elements we have only a hazy idea of where it lies. The third frontier to the Chart of the Nuclides is the production of superheavy elements. This represents the limit in total mass and will be determined by the increasing tendency to fission or alpha decay as Z increases, which is delayed by shell effects. At present we do not know where this boundary lies.

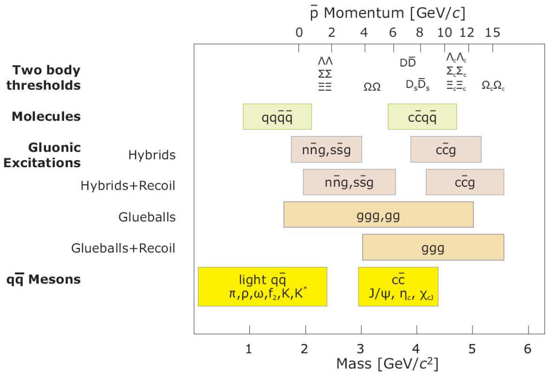

Figure 3. Hadron mass range accessible by the PANDA experiment.

3.2. PANDA

One of the attractions of the FAIR facility is the provision of cooled antiproton beams of unprecedented intensity and quality, stored in the High Energy Storage Ring (HESR). The HESR will deliver 10^{11} stored and stochastically or electron

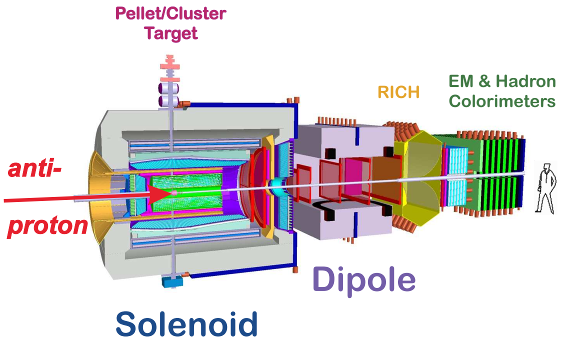

Figure 4. The PANDA experiment. The antiproton beam enters from the left and hits the target one quarter into the superconducting solenoid. Particles emitted in the forward direction are momentum analysed by a dipole magnet. The setup is 12 m long.

cooled antiprotons at luminosities up to $2 \cdot 10^{32}$. Its energy resolution will lie between 10^{-5} and 10^{-4} at energies between 3 and 14 GeV. Antiproton annihilation in this energy regime will produce strange and charmed quarks in addition to large amounts of gluons.

The PANDA experiment (cf. Ref. [5]) will address a number of key physics issues such as a better understanding of quark confinement by comparing precision measurements of electromagnetic and hadronic charmonium decays with Lattice-QCD calculations, and the search for, and precision spectroscopy of, charmed hybrid mesons, glueballs and other exotic hadronic states. (cf. Fig. 3).

PANDA has been designed to achieve almost full 4π hermiticity (cf. Fig. 4). It is based on two magnetic spectrometers that analyse the momentum of the emitted charged particles in a wide range from 100 MeV/c to 8 GeV/c. The superconducting target solenoid surrounds the interaction region and has a forward opening of 22^0 to allow high momentum particles enter the forward dipole spectrometer. Since many hadron decay channels include charmed mesons, a micro vertex detector with excellent position resolution is required. Other important components of PANDA are the electromagnetic calorimeters with good energy resolution down to very low energies, and the hadron calorimeter. To separate kaons from protons and muons, particle identification using various time-of-flight and Cherenkov detector systems will be performed.

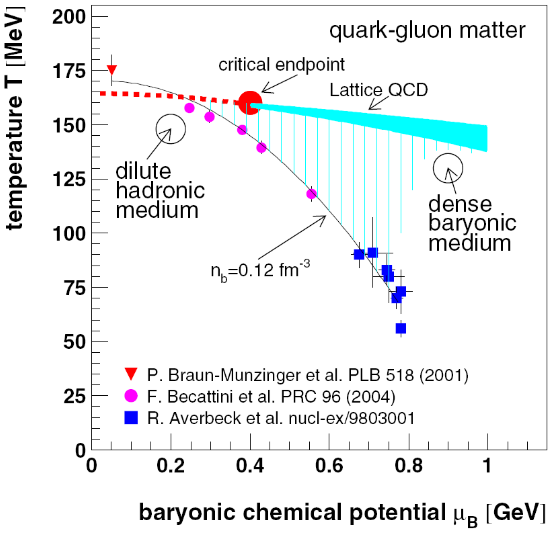

Figure 5. Phase diagram of strongly interacting matter as a function of temperature and baryon chemical potential (density), taken from Ref. [3,6]

3.3. CBM

The third large research programme at FAIR involves the use of high intensity heavy ion beams at energies of 10-45 GeV/u. The Compressed Baryonic Matter (CBM) experiment (cf. Ref. [6])is intended to simultaneously measure hadrons and leptons. Its high rate capability will allow us to study rare particle probes of the dense medium. Highlights will be the study of vector mesons and their possible in-medium mass modification, the near threshold production of charmonium states and open charm - sensitive to the possible onset of chiral symmetry restoration, and the search for exotic multiquark states, especially kaon clusters and strangelets.

As a result of the high temperatures and densities that may be achieved in high energy nuclear collisions, it may be possible to melt nuclear matter into a de-confined phase of quarks and gluons, where hadrons cease to exist. Such a state of matter is believed to have existed until around $10\,\mu s$ after the Big Bang. It may also exist today in the core of some dense stellar objects such as neutron stars. High quark (and gluon) densities may be achieved by colliding nuclei at high energy. This is the approach that has been undertaken at CERN and RHIC. However, at the highest energies the incoming nucleons do not come to rest in the collision, creating a dense medium that contains an equal number of quarks and anti-quarks. This corresponds to a low net-baryon density and is pertinent to the study of matter in the early Universe. At lower energy, the stopping power of the nucleus increases, leading to a system with a high net-baryon density. This is more relevant to the study of neutron stars. Unique to the experiments that will be performed at FAIR, is the possibility to study the nuclear phase diagram in the region where there is predicted to be a critical point (cf. Fig. 5). This marks the end of a phase boundary, where the transition ceases to be of first order and changes to be of crossover type. Non-statistical fluctuations of quantities such as quark flavour are expected in the vicinity of a critical point and observation of these may provide the best experimental evidence of a phase transition in nuclear matter.

4. TIMELINES

Signing the FAIR convention is planned in spring/summer 2007. Construction of the facility will start shortly afterwards. Its completion will take place in three phases with the CR, NESR and Super-FRS commissioned first, the SIS 100, RESR and HESR with stochastic cooling second, and the SIS 300 and HESR with electron cooling last. The whole facility is planned to be fully operational by 2015.

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