Executive summary:
FLAIR, a Facility for Low-energy Antiproton and Ion Research

Overview

The future FAIR facility will produce the highest flux of antiprotons in the world. Within the planned complex of storage rings, it is possible to decelerate antiprotons to about 30 MeV kinetic energy, opening up the possibility to also create low-energy antiprotons. This led to the formation of a new collaboration with the aim to create a next-generation facility for low-energy antiprotons called FLAIR. The fact that many of the accelerators and experimental facilities planned can be equally well used for low-energy highly charged ions (HCI) makes it possible to exploit synergies in order to create a unique facility for low-energy antiprotons and HCI. This has naturally led to a strong entanglement between the FLAIR and the SPARC collaborations.

Low-energy antiproton physics is currently being done at the Antiproton Decelerator (AD) of CERN, Geneva. Due to the low intensity of $\sim 10^5\ \bar{p}$/s and the availability of only pulsed extraction, the physics program is limited to the spectroscopy of antiprotonic atoms and antihydrogen formed in charged particle traps or by stopping antiprotons in low-density gas targets. Furthermore, the output energy of the AD (5 MeV kinetic energy) is still significantly higher than the < 100 keV energy best suited for these experiments. A next-generation low-energy antiproton facility must overcome these limitations by providing cooled beams at higher intensities and a factor 10 or more lower energy. In addition it should have the possibility of slow (i. e. continuous) extraction, which will allow nuclear/particle physics type experiments requiring coincidence measurements to be performed. Here, we describe a facility consisting of two storage rings, a magnetic (LSR) and an electrostatic (USR) one, and a universal trap facility (HITRAP).

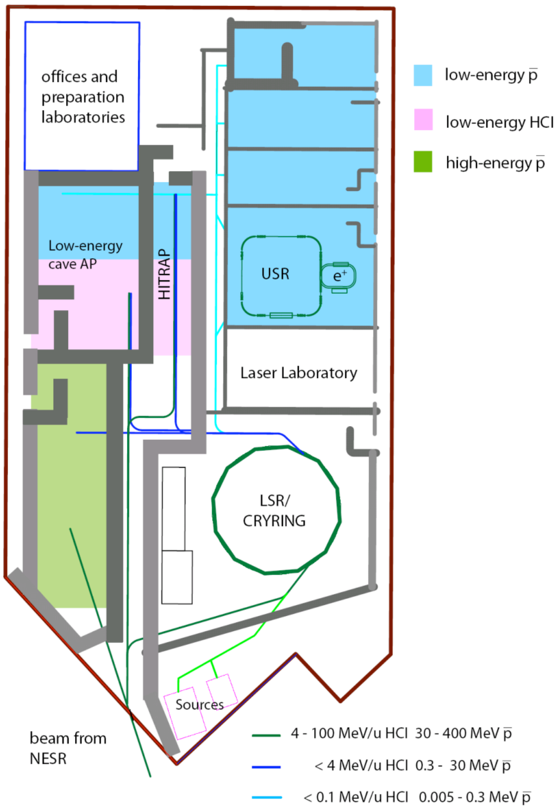

Fig. 1: Layout of the FLAIR facility

These components of the facility (cf. Fig. 1) can provide stored as well as fast and slow extracted cooled antiproton beams at energies between 30 MeV and 300 keV (LSR), between 300 keV and 20 keV (USR), and cooled particles at rest or at ultra-low eV energies (HITRAP). The whole structure will also be used to study highly charged ions, including storing, cooling (LSR, USR) and trapping them in Penning traps like HITRAP and investigating them in the new Low-energy HCI cave. Here, highly charged ions of energies from 130 MeV/u down to < 100 keV/u can be used for experiments. The physics with HCI in HITRAP and the new Low-energy HCI cave are part of the program of the SPARC collaboration, but HITRAP can be equally well used to trap, cool and extract low-energy antiprotons. It is planned to extract antiprotons at sub-keV energies from HITRAP and to transfer them to the low-energy experimental caves (light blue areas in Fig. 1). In addition, low-energy antiprotons can be delivered to an experimental area on top of the HITRAP cave and to the Low-energy HCI cave for the experiments described below.

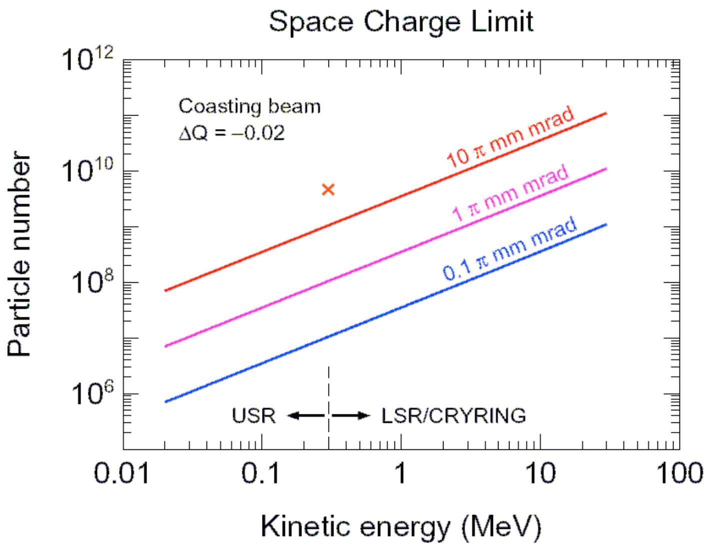

Fig. 2: Space charge limits in storage rings for different emittances. The orange cross corresponds to a recent measurement in CRYRING

At low energies, the number of particles in a storage ring is limited by the space charge. Fig. 2 shows estimated space charge limits in the energy range of the LSR and USR which were confirmed by a measurement performed recently at CRYRNG at the Manne Siegbahn Laboratory in Stockholm, Sweden. CRYRING, which will stop operation in Stockholm, is considered to be the best solution for LSR after necessary modifications. Assuming a duration of the antiproton production and deceleration cycle of about 20 seconds, average rates of typically 10^6 antiprotons per second can be achieved at beam emittances of 1-5 π mm mrad. The same rates will be available for antiprotons extracted from HITRAP, and inside USR effective collision rates of 10^{10}–10^{12}/s can be achieved because of the revolution frequency of MHz. Thus, the available antiproton rates at FLAIR will be significantly larger than the ones currently available which leads to a factor 100 higher rate of antiprotons trapped in charged particle traps or stopped in low-density gases for precision spectroscopy.

Physics program with low-energy antiprotons

The physics of FLAIR covers a wide range in atomic, nuclear and particle physics and has potential medical applications. Precision spectroscopy of antiprotonic atoms and antihydrogen is the current topic of the Antiproton Decelerator (AD) at CERN. The main goal here is to study fundamental symmetries and interactions by providing high-precision data of particle and antiparticle properties for tests of CPT symmetry and QED calculations. Until 2010 initial results on spectroscopy are expected from the AD, but the ultimate goal of reaching accuracies similar to hydrogen requires the trapping and laser-cooling of antihydrogen atoms which will take a long time to achieve. Once trapped and laser-cooled antihydrogen is available, other challenging experiments can be performed. The gravitation of antimatter is a long standing question that has never been answered experimentally, because in the case of charged particles, gravitational effects are covered by the many orders of magnitude stronger electromagnetic interaction. Collisions between antihydrogen and matter atoms as well as the creation of larger antimatter systems like $\overline{H}^{+}$ (one antiproton and two positrons, equivalent to the well known H^- ion) are of big interest for atomic collision theory.

Atomic collision physics will greatly benefit from the availability of ultra-slow, cooled antiproton beams in storage rings. This will enable for the first time ever the detailed study of ionization processes with antiprotons in kinematically complete experiments. The energy loss can be investigated at ultra-low energies to answer open questions about the velocity dependence in this regime. Antiprotons are best suited for such studies, because unlike protons their charge is not screened by electrons which make the theoretical treatment very difficult. The very short interaction time of less than femtoseconds for antiproton energies above 1 keV makes antiprotons a perfect and unique tool to study many-electron dynamics in the strongly correlated, non-linear, sub-femtosecond time regime, the most interesting and, at the same time, most challenging domain for theory.

In nuclear physics, the antiproton is used as a hadronic probe to study the nuclear structure. X-ray spectroscopy of the low-lying states of $\overline{p}p$ or other light atoms gives important information on the nucleon-antinucleon interaction in the low-energy limit, where scattering experiments cannot provide precise values. These data are vital for the improvement of QCD calculations in the low-energy (hence non-perturbative) region. X-ray spectroscopy of heavy antiprotonic atoms can be used to obtain information about the density ratio of neutron and protons at the nuclear periphery, i.e. to investigate neutron halo or skin effects. The PS209 experiment at LEAR has in this way provided benchmark data for nuclear structure calculations over a wide range of nuclei. This technique is much more sensitive than others like total absorption cross section measurements, and further systematic measurements with stable isotope targets will provide a more complete and systematic picture of the nuclear surface. Since halo effects are expected to be more pronounced in nuclei with a large neutron excess which are unstable, the application of this technique to unstable radioactive ions available at FLAIR via the SuperFRS will generate important contributions to the study of the structure of nuclei far from stability.

Very recently a new idea has emerged to use stopped antiprotons to produce nuclei containing two deeply bound negative kaons, where the binding energy of the K^- is expected to be in the order of 200–400 MeV. Double antikaonic nuclear clusters are predicted to have densities exceeding ~5–6 times the average nuclear density $\rho(0) = 0.17\ \mathrm{fm}^{-3}$, thus reaching in the phase diagram of hadronic matter conditions were phase transitions to kaon-condensation or colour superconductivity at low temperature may be reached. Using stopped antiprotons the two K^- could be produced under ideal kinematical conditions, i.e. with small momentum transfer to the nuclei. The study of double antikaonic nuclear clusters would require a large 4π detector that could be placed in the high-energy antiproton area (light green in Fig. 1).

The study of baryon-baryon interactions as a basic tool for investigations of the strong interaction can be extended to the hyperon sector, where much less data exist than in the nucleon sector. Especially few data exist on strangeness S= -2 systems. Stopped antiprotons are very efficient for the production of S=-2 systems via the double strangeness and charge exchange reaction ($\overline{K}^*$, K). With a sizeable branching ratio the annihilation of antiprotons results in the production of a $\overline{K}^*$ "beam" which interacts with another nucleon via $\overline{K}^*\, N \rightarrow K\, \Xi$. The momenta of the $\overline{K}^*$ are well matched for the production of slow Ξ particles which undergo efficient Ξ N interactions. The proposed studies will result in detailed information of S=-2 baryonic and possible dibaryonic states.

Recently, interest has been shown in the medical application of antiprotons for tumour therapy. This comes from the fact the antiprotons, in addition to depositing energy via their energy loss like other charged particles, annihilate when stopped in material. The annihilation produces residual nuclear fragments of high charge and low energy, which deposit a large biological dose in the immediate surrounding of the $\overline{p}$ stopping distribution. Since the cooled low-emittance antiproton beams can be stopped in a well-defined region, the presumably large energy deposited locally makes them a suitable tool for tumour therapy. A test experiment is under way at the AD of CERN and, if this effect is confirmed, the method can be extended at FLAIR where the high-energy antiproton beams (50 - 300 MeV) needed to penetrate deep enough into human tissue are available directly from the NESR.