PROCEEDINGS OF SCIENCE

Antiproton-Nucleus Reactions at PANDA

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The study of antiproton annihilations on nuclei is one of the major physics topics of the PANDA experiment at FAIR, which is presently in the phase of construction. This articles presents, besides the description of the facility and the experiment, selected physics topics which will be addressed by PANDA.

Sixth International Conference on Quarks and Nuclear Physics,
April 16-20, 2012
Ecole Polytechnique, Palaiseau, Paris

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PoS(QNP2012)161

1. FAIR - The Facility for Antiproton and Ion Research

The **F**acility for **A**ntiproton and **I**on **R**esearch (FAIR)[1] is currently constructing its so-called modularized start version. FAIR extends the existing accelerators of the GSI Helmholtzzentrum für Schwerionenforschung[2]. In Fig. 1 the layout of FAIR is shown together with the existing GSI.

A new ingredient at the Darmstadt site is the possibility to produce antiprotons ($\bar{\mathrm{p}}$). The accelerator chain comprises a new proton linac, a synchrotron (SIS18)[3] and another, also new, synchrotron (SIS100), which accelerate a primary proton beam to 30 GeV. The protons are extracted from SIS100 and shot onto a production target. The there produced antiprotons are transported into a chain of two storage rings, where they are collected and pre-cooled. Finally, at a fixed momentum of 3.5 GeV/c the antiprotons can be injected into the HESR[4]. The HESR accelerates or decelerates the antiprotons (dynamic range from 1.5 to 15 GeV/c) and stores them for experiment, including also additional cooling. The maximum momentum corresponds to 5.5 GeV/c^2 in the $\bar{\mathrm{p}}\mathrm{p}$ system. Eventually the HESR can be operated in two modes:

(1) High resolution mode: the momentum resolution reaches $\frac{\delta_p}{p} = 2 \cdot 10^{-5}$ at a luminosity of $2 \cdot 10^{31}\mathrm{cm}^{-2}\mathrm{s}^{-1}$.

(2) High luminosity mode: a luminosity of $2 \cdot 10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ is provided at a momentum resolution of $\frac{\delta_p}{p} \sim 10^{-4}$

The design values given above however will not be fully reached in the start version of FAIR. Though the PANDA experiment (see next section) will be served exclusively by the HESR to study $\bar{\mathrm{p}}$ annihilations on an internal target.

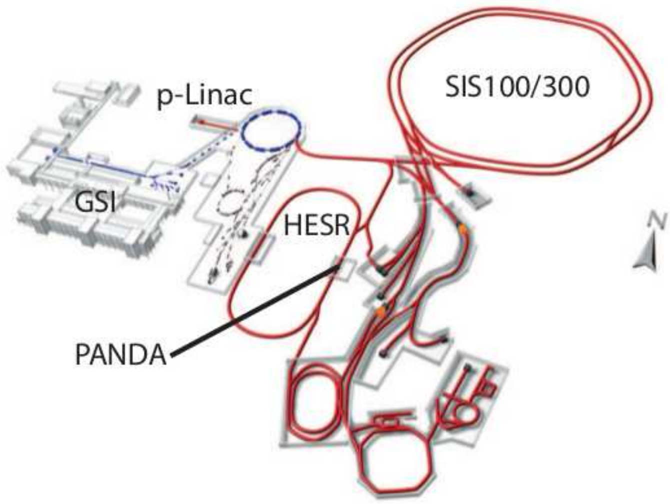

Figure 1: Layout of the FAIR accelerator complex (red) as extension of the existing GSI accelerators (blue). The location of the PANDA experiment is indicated, too.

[1] http://www.fair-center.org

[2] http://www.gsi.de

[3] 18 Tm bending power

[4] High Energy Storage and Synchrotron Ring

2. The PANDA Experiment

The PANDA [1] detector is shown schematically in Fig. 2. PANDA is a fixed target experiment: the interaction region is realized by a joint cross between the beam pipe (left-right) and a target pipe (top-bottom). The target itself is a beam of frozen pellets (H_2,D_2,...), a cluster jet (hydrogen and heavier gases) or a foil/wire (solid target material). The PANDA apparatus consists out of a target spectrometer with a 2 T solenoidal magnet, and a forward spectrometer with a 2 Tm dipole. The dipole bends the beam out of the 0° line in the $x-z$ plane, which allows to measure reaction products down to 0°.

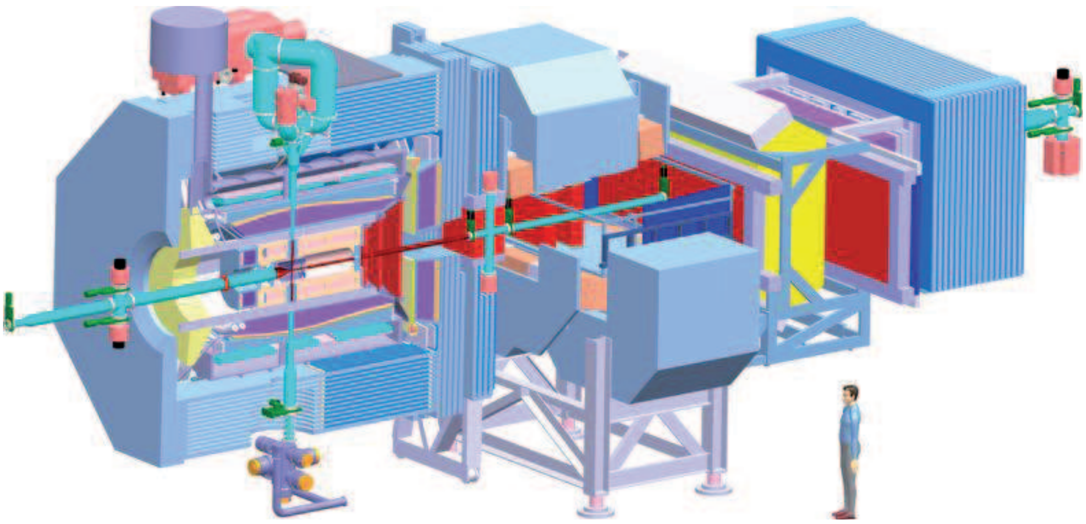

Figure 2: The PANDA detector. For a brief description of the components see text.

The PANDA detector aims to measure the charged and neutral reaction products of the $\bar{\text{p}}$ annihilations as complete as possible. The closest detector to the interaction point is the Microvertex Detector (MVD). It is a detector built out of silicon pixel/silicon strip sensors and gives a spatial resolution of $\sim 50\mu$m, which is important for the reconstruction of decay vertices of short lived particles like e.g. the D_S meson. The central tracking detector, outside the MVD, is made out of straw tubes. This device measures charged particle momenta with $\sim 1\%$ resolution. In addition, the information from $\frac{dE}{dx}$ can be used for particle identification, and decay vertices of longer lived particles can be reconstructed in the central tracker. The forward angles which are not measured by the central tracker are covered by several layers of GEM[5] foils. The particle identification in the target spectrometer is done by a Cherenkov detector barrel, using the DIRC[6] technique, and a forward disc. Above 1 GeV/c, the DIRC can distinguish charged pions, kaons and protons. Attached to the DIRC, a time of flight detector using small scintillator tiles is foreseen. The electromagnetic calorimeter (EMC), which consists out of a barrel part, a forward and a backward endcap as well, measures photons from 1 MeV to 10 GeV energy. The energy resolution is $\frac{\sigma_E}{\sqrt{E}} < 2\%$. A muon detection system, instrumenting the iron yoke of the solenoid, is the most outside detector of the

[5] Gas Electron Mulitplier

[6] Detection of Internally Reflected Cherenkov light

target spectrometer. For the hypernuclear physics setup, the backward endcap of the calorimeter will be removed. This particular experiment (see section 3) uses a more upstream location of the target, and the backward angles are covered by Germanium semiconductor detectors to measure γ rays.
In the forward spectrometer part, several tracking stations, an electromagnetic and a hadron calorimeter will be installed.
Technical design reports (TDR) are approved for the magnets [2] and the EMC [3], and submitted for the MVD, the straw tube tracker [4] and the targets. The TDRs of the remaining subsystems are to be submitted within the year 2012 (with only a few exceptions). See Ref. [1] for the current status.
The installation on site at FAIR is foreseen for the year 2016, after the completion of the civil construction. After the commissioning of the accelerators and the detectors, the start of data taking is envisaged for 2018.

3. Physics in $\bar{p}$A Reactions

An unique feature of the PANDA experiment is the possibility to perform antiproton annihilations on nuclei, thus the study of processes in the presence of a nuclear medium (at normal nuclear matter density). Nuclear targets in PANDA can be made from gases (D_2, N_2, Xe, ...) applied as frozen pellets or as cluster jets, or solid material (thin wires, foils). The achievable luminosity in the case of nuclear targets is lower as the quoted values in section 2, dependent on the nuclear charge Z and the beam momentum. E.g. for a $\bar{p}$ of 1.5 GeV/c interacting with a copper target, a luminosity of $\sim 10^{29}\text{cm}^{-2}\text{s}^{-1}$ can be reached which is significantly lower as for the $\bar{p}p$ case.

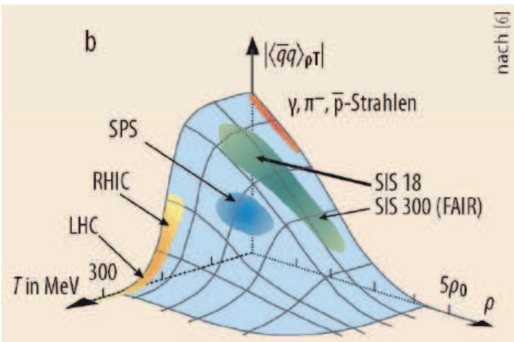

Figure 3: The expectation value of the light quark condensate $|\langle \bar{q}q \rangle|$ as a function of temperature T and density ρ. The relevant area for $\bar{p}$'s is marked in orange. The figure has been taken from [5].

Fig. 3 should illustrate that using a $\bar{p}$ beam ($T = 0$) on a nucleus ($\rho = \rho_0$), the expectation value of the light quark condensate drops by ca. 20%. According to Ref. [6], this drop might lead to in-medium modified particle properties. Such in-medium effects can manifest themselves in mass shifts with respect to the free hadron masses, broadening of resonances (i.e. their lifetimes change) and the formation of bound states. The experimental search for such effects is being pursued in the light and strange quark sector since many years, see e.g. [7]. At HESR-PANDA the studies will be extended into the sector of charmed hadrons.

The mass of the D meson in nuclear matter has been addressed in various theory works, like [8, 9, 10]. An attractive potential for the D^+ and a repulsion for the D^- is predicted. Ref. [8] pointed out that a drop of the D meson mass in nuclear matter should lead also to a lowering of the $D\bar{D}$ threshold. A charmonium state like the Ψ' which in vacuum lies below that threshold could consequently decay into $D\bar{D}$. An in-medium mass shift of the charmonium states themselves is

assumed to be small.
An attractive potential should also allow the formation of bound states between D mesons and the nucleus, provided the potential depth and the width of such a system allow for a binding. In Ref. [11] a number of possible D^0-nucleus bound states have been calculated. The experimental difficulty is the large momentum in the laboratory frame of charmed hadrons, hence the preparation of a "slow" D meson in the nucleus is a tricky undertaking. In the case of D^- mesic nuclei, the Coulomb potential might assist a binding, and if such an object decays only weakly, the probability to detect it increases.

The possibility to determine the J/Ψ-N cross section (i.e. the dissociation of the $c\bar{c}$ system in a hadronic environment) is discussed i.a. in [12] and briefly reported in the following paragraph.

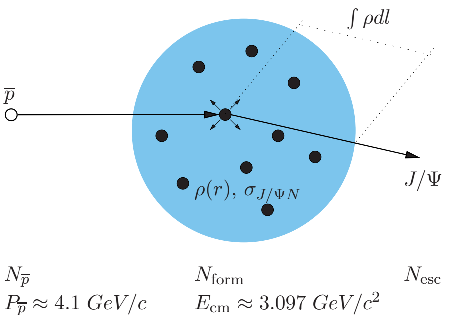

Figure 4: Schematic illustration of the determination of the J/Ψ-Nucleon dissociation cross section using a $\bar{p}$-nucleus reaction.

The reaction $\bar{p} + A \to J/\Psi + X$ with a subsequent J/Ψ decay into a dilepton pair is used for this measurement. Fig. 4 illustrates the procedure. The experiment measures the number N_{esc} of J/Ψ's which escape from the nucleus. With a Monte-Carlo calculation the number N_{form} of originally formed J/Ψ's is estimated, and the average nucleon density seen by the J/Ψ on its path out the nucleus is calculated. Knowing these quantities, the J/Ψ-N cross section $\sigma_{J/\Psi N}$ can be estimated:

$$N_{esc} = N_{form}\left(1 - \sigma_{J/\Psi N}\left\langle \int \rho \cdot dl \right\rangle\right) \qquad (3.1)$$

A simulation demonstrating that the necessary background suppression is achievable with PANDA has been presented earlier [13].

The procedure is in principle applicable for other $c\bar{c}$ states, too. For the J/Ψ case a rate of several hundred per day has been estimated [12]. The smaller production cross section and the branching ratio into dileptons has to be considered for other $c\bar{c}$ states.
A further topic which will be addressed by PANDA concerns the nuclear potential for antibaryons (like $\bar{\Lambda}, \bar{p}$) and $\bar{K}$. Proton knock out reactions can be used to implant a low recoil momentum $\bar{h}$ into a nucleus. E.g. for the $\bar{p}$, Ref. [14] predicts a very deep potential. Measuring a recoil proton under $\simeq 0°$, its missing mass distribution carries information on the $\bar{p}$ nuclear potential. Moreover, a recoil proton momentum larger than the incident $\bar{p}$ momentum would be a very sensitive signature for an attractive $\bar{p}$ potential.

In a similar way, the potential of antihyperons can be addressed. The left panel of Fig. 5 illustrates the principle. An antihyperon is quasi-bound in a nucleus, and the corresponding hyperon is measured close to 0°. In the case of higher momentum hyperons (right panel of Fig. 5), the comparison of the transverse momentum distributions of the hyperon and the anti-hyperon might show the difference of the respective potentials.
As already mentioned in section 2, another application of $\bar{p}$A reactions is the production of hypernuclei, in particular double Λ hypernuclei. At PANDA, a two step production is foreseen. A $\bar{p}$ of 3

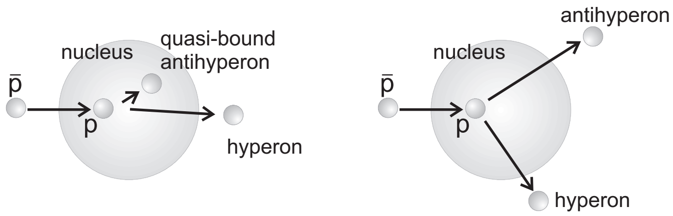

Figure 5: Production of a hyperon-antihyperon pair in a $\bar{p}$p annihilation in a nucleus. The antihyperon can form a quasi-bound state (left) oder escape from the nucleus (right).

GeV/*c* hits a primary target (carbon) and produces a $\Xi\bar{\Xi}$ pair. The Ξ^+ is either detected directly or via charged kaons produced in interactions of the Ξ^+ inside the primary target. It serves as a tagger for $\Xi\bar{\Xi}$ production. The Ξ^- will be captured in the atomic orbit of a secondary target, cascade down the atomic energy levels till reaching the nucleus. Here, eventually it reacts with a proton into a pair of Λ hyperons. This reaction is accompanied by the emission of a γ ray of 28 MeV which has to be measured to confirm the presence of $\Lambda\Lambda$. A more detailed description of the experiment can be found in Ref. [15] and [13].

Acknowledgement

The author acknowledges the support by the HadronPhysics3 initiative of the 7^{th} Framework Program of the European Union and the Austrian Science Fund FWF.

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