The PANDA Physics Program: Strangeness And More

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Abstract. The physics program of the PANDA experiment at FAIR is illustrated, with a particular attention to the planned activity in the field of the doubly strange systems. The investigation of these systems can help, among others, to shed light on the role of the hyperons in the composition of the neutron stars. The great advantages that can be reached in the field of the charmed systems and nucleon structure by using high quality and intense antiproton beams are also recalled.

INTRODUCTION

The original goal of the FAIR (Facility for Antiproton and Ion Research) project is to provide very intense beams of ions and antiprotons($\overline{p}$) of high quality in a new site close to the GSI laboratory in Darmstadt, Germany [1]. Four scientific pillars are in the scientific planning of FAIR, each one aiming to explore specific fields of physics: APPA, dedicated to atomic, plasma and applied physics; NUSTAR, to nuclear structure and astrophysics; CBM, to QCD and hot and dense hadronic matter at low energy; PANDA, to doubly strange systems, charm physics and nucleon structure studies [2].

FAIR will produce antiprotons by using high-energy protons, which will be accelerated in the SIS100 synchrotron and imping onto a Cu target. Then they will be collected in the Collector Ring (CR), at a rate of 10^7 s^{-1}, cooled to 3 GeV/c and sent to the High Energy Storage Ring (HESR),where they will be stored in a bunch of 10^{10} antiprotons [3]. This bunch will be accelerated or decelerated to the desired momentum, in the range 1.5 - 15 GeV/c. The targets used by PANDA for the investigated reactions will be located inside the beam pipe of the HESR: they will be thin solid targets for the hypernuclear measurements, and pellet/cluster-jet targets for the other QCD studies. After the HESR antiproton content reduces to few percent, the beam will be dumped and the collection-cooling- accumulation-acceleration procedure will be restarted [4].

In addition to the wide momentum range, the design of the antiproton beam at HESR foresees two other important features: a high momentum resolution δp/p $\approx 10^{-5}$ - 10^{-4} and the above-mentioned high number of stored antiprotons. In a second stage of FAIR the construction of a further ring, RESR, is foreseen, in which bunches of 10^{11} antiprotons will be stored, accelerated/decelerated to the desired momentum and injected into HESR. In this future configuration a luminosity up to 10^{32} cm^{-2} s^{-1} is expected with a hydrogen cluster-jet target of surface density $\approx$ 4x10^{15} atom/cm^2 . Thanks to these features, the antiproton beam of the HESR will reach two goals. On one side, using a new technique, the production rate of Doubly Strange Systems (DSS) will increase considerably with respect to the past, as explained in the second section of the present paper. On the other side, the resolution in the measurements of mass and width of the known resonances and in the scanning of the wide energy region, where new hadronic states could be found, will greatly improve, as reported in the third section of the present paper.

Concerning DSS, the present worldwide data are very scarce [5] and only recently, the advent of the new JPARC facility, which provides kaon beams of unprecedented intensity, opens perspectives for new data. On the other hand, the physics of the fundamental interactions in DSS is interesting under the aspect of the strong interaction and can help, among others, the understanding of the evolution of the neutron stars. Therefore, a statistically significant collection of data, as foreseen in PANDA, is welcome.

Other open problems related with the understanding of QCD in the transition between perturbative and non-perturbative regime could be addressed by studying antiproton annihilations since the antiproton-proton entrance channel strongly couples with the gluonic components of the produced hadrons and/or quarkonium states. Moreover, the range of the quantum numbers of the produced systems is wider than the low spin states allowed in electron-positron colliders. Therefore, the PANDA experiment will be able to perform a systematic study of the charmonium energy range producing complementary information with respect to the present running facilities.

PHYSICS OF THE DOUBLY STRANGE SYSTEMS

The high intensity and the good momentum resolution of the HESR beam, suggested the PANDA Collaboration to investigate the sector of Double Hypernuclei (DH), in order to overcome the lack of data in this field, which is due to the difficulty to create systems with double strangeness [6]. The only way to effectively produce DH's is to stop a Ξ^- hyperon in ordinary matter, and in the past this was done by using kaon beams. The innovative idea of PANDA is to use antiprotons instead of kaons [7]. As it will be illustrated in the following, the PANDA setup will allow detecting, in addition to the DH's, also the hyperatoms and Ξ^--hypernuclei formed before DH's. This technique will permit to investigate the whole set of experimentally accessible Doubly Strange Systems (DSS) providing a wide amount of information.

Concerning the hyperatoms, their formation proceeds through the absorption of a Ξ^- in a high atomic level ($n \approx 100$), followed by a cascade down to low levels accompanied by X-rays emission. In the atomic orbits closest to the nucleus, the Ξ^- feels also the strong force which combines to the Coulomb one, shifting and broadening the atomic energy levels. By measuring the shift and broadening of the energy of the X-rays emitted in the transition to the last level n_{abs}, it is possible to fix the parameters of the nuclear potential in the periphery of the nucleus [8, 9].

A Ξ^--hypernucleus can be formed, with the emission of a γ-ray, when the hyperon is absorbed by the nucleus. The absorption of a Ξ^- inside a nucleus creates a hypernucleus with atomic number decreased by 1 and baryon number increased by 1 with respect to the original nucleus, through the reaction:

$$\Xi^- +^Z A \rightarrow^{Z-1}_{\Xi} A + \gamma \tag{1}$$

The measurement of the spectrum of the γ's of Equation 1 can give information about the structure of the hypernucleus itself.

Considering the Y-N interactions:

$$\Xi^- N \rightarrow \Xi^- N; \Xi^- p \rightarrow \Xi^0 n; \Xi^- p \rightarrow \Lambda\Lambda \tag{2}$$

the long range OBE mechanism only permits the exchange of non-strange and integer-isospin mesons (π, η, ρ, ω...) in the first two reactions of Equation 2, and only strange and half-integer-isospin mesons (K, K*) in the third one. Data about the relative rates of the above reactions could be obtained by reconstructing with high statistics the final states of the Ξ^--hypernucleus, thus allowing to check the predictions of OBE and other models. It must be remarked that the non-mesonic weak interactions $\Xi^- N \rightarrow \Lambda N, \Sigma N$ are strongly suppressed in the nucleus with respect to the strong processes in Equation 2.

Double Hypernuclei could be eventually produced when the third reaction of Equation 2 occurs and both Λ's stick up to the residual nucleus (or to the same fragment in case the excess of energy breaks it up [10]). This reaction is unique to shed light on the YY interaction. In fact, if the detector system is able to reconstruct the final state of $\Xi^- p \rightarrow \Lambda\Lambda$, one can measure the binding energy $B_{\Lambda\Lambda}(^A_{\Lambda\Lambda}Z)$ of the ΛΛ-hypernucleus (or hyperfragment) formed by the A nucleons plus two Λ's. If the binding energy $B_\Lambda(^A_\Lambda Z)$ of the single hypernucleus ($^A_\Lambda Z$) is known, (it is noteworthy that several single hypernuclei are well known) one obtains the energy $\Delta B_{\Lambda\Lambda}$ of the ΛΛ interaction (called "separation energy"):

$$\Delta B_{\Lambda\Lambda} = B_{\Lambda\Lambda}(^A_{\Lambda\Lambda}Z) - 2B_\Lambda(^A_\Lambda Z) \tag{3}$$

In addition to the ΛΛ strong interaction, (it is interesting to remark that in $\Lambda\Lambda \rightarrow \Lambda\Lambda$ the OBE occurs only through non-strange, zero-isospin mesons η, ω...) also the Hyperon Induced Non Mesonic Weak (HINMW) decay: $\Lambda\Lambda \rightarrow \Lambda n, \Lambda\Lambda \rightarrow \Sigma^- p$, can occur (only) in DH. In these decays, the momentum of the exiting nucleons and hyperons is very high (≈ 430, 320 MeV/c) and, therefore, they are easy to be detected by a proper magnetic spectrometer like PANDA [11].

Summarizing, the Ξ^--nucleus potential, the Ξ^-N and $\Lambda\Lambda$ strong interaction and the weak interaction in $\Lambda\Lambda$ HINMW decay are strangeness topics that PANDA can investigate. The intrinsic interest of this kind of physics further increases by looking at the importance of the hyperon properties in the models that describe the neutron stars, as discussed in the next section.

To fulfill the goal of investigating the DSS, PANDA plans to produce hyperons by using antiprotons in a storage ring instead of kaons extracted beams. Briefly, the two reactions:

$$\overline{p} + N \rightarrow \Xi^- + \overline{\Xi} \tag{4}$$

$$K^- + p \rightarrow K^+ + \Xi^- \tag{5}$$

produce a Ξ^- hyperon (quasi-free if the target nucleon is bound in a nucleus) using antiprotons and kaons respectively. The hyperon is then brought to rest and absorbed in another nucleus forming a doubly strange hypernucleus: a double hypernucleus can be formed from the conversion reaction if both Λ's stick to the nucleus (fragment).

The advantages in terms of intensity and resolution of using an antiproton ring to produce hyperons through the reaction of Equation 4 have been already pointed out in the Introduction. Unfortunately, the use of a ring imposes constraints on the target to be placed inside the beam pipe, which must be very small, in order to not destroy the beam. This problem has been solved by planning a two-target technique, which consists in inserting only a very thin target, dedicated to the hyperon production, inside the beam pipe and placing a second target, dedicated to the hypernucleus production, together with the other detectors, outside the beam pipe [7]. With this configuration the choice of the internal target for maximizing the stopped Ξ^- rate is independent upon the design of the external target, allowing different nuclei to be explored with the same efficiency of the hyperon production.

A suitable geometry [12] of this setup guarantees a rate of 2.2 10^{-3} stopped Ξ^- in the external target per each Ξ^-, which is produced in the internal one.

Prototypes of the internal target, shaped as a thin filament, have been already made and tested [13] while the design of the external target is in progress. The detection of the X and γ rays, emitted by hyper-atoms, Ξ^- hypernuclei and Double Hypernuclei, will be performed by means of an existing HPGe Cluster array added to the ordinary PANDA magnetic setup. The presence of a fringing magnetic field in the region where the X and γ - rays detectors are located does not affect appreciably their efficiency and resolution, as tests demonstrated [14, 15]. The overall efficiency (single detectors, reconstruction software) is under test: the preliminary results indicate an expected rate of DH events between 50 and 100, in 3 months. This performance, if confirmed, would provide an unprecedented statistics of DSS data.

STRANGENESS IN NEUTRON STARS

Hyperons are important components of the Neutron Stars (NS) in the regions where the density overcomes twice the saturation nuclear density $n_0 \approx 0.16$ fm^{-3}. The core of the NS is largely unknown and several possible phases are candidates as core matter: pion and kaon condensation, nucleon, resonances and hyperon mixing, pure strange quark stars. The hyperons are the first exotic components that appear when the density increases. As reported by Schaffner-Bielich [16], a free gas of electrons, muons and hadrons can contain only Σ^- and Λ hyperons, all the other ones require unrealistic densities of NS. This situation changes drastically if the nucleon-nucleon (NN), nucleon-hyperon (YN) and hyperon-hyperon (YY) interactions are taken into account: including these interactions, the onset of Σ^-, Λ and Ξ^- is approximately located at $1.8n_0$, $1.92n_0$ and $2.44n_0$.

Several models describe the hyperon onset: Relativistic Mean Field (RMF), Non-Relativistic Potential (NRP), Quark-Meson Coupling (QMC), Relativistic Hartree-Fock approach, Brueckner- Hartree-Fock calculations, SU(3) based Chiral Effective Lagrangian, G-matrix-based Effective Interaction approach [17]. In these models, the composition of the NS depends strongly on the potential depths [16], whose values come from the data of the hyperatoms and hypernuclei.

The mass of the NS has a maximum M_{MAX}, which is controlled by the stiffness of the high-density equation of state (EoS). The presence of hyperons and their interactions strongly influence the stiffness. Including non-interacting hyperons in the NS composition, M_{MAX} reduces to less than 1.4 solar masses ($M_\odot$), while a pure neutron, proton and lepton star can reach $2.3M_\odot$ [16]. If a repulsive YN interaction is switched on, M_{MAX} slightly increases, but not enough to be consistent with the observation of the PSR J1614-2230 mass $M = (1.97 \pm 0.04)M_\odot$ [18]. The proposed introduction of 3-body forces, NNY, NYY and YYY, could solve this puzzle (so called "hyperon puzzle", [19]). Other solutions include also the presence of the Δ resonance, with interactions NΔ and YΔ [20].

The presence of hyperons in dense star matter plays another important role in regulating the stability of the r-modes of the pulsars, when the rotation brings the neutron star out of the β-equilibrium in some regions. To recover the equilibrium, the weak non-mesonic decays:

$$\Lambda N \leftrightarrow NN, \Sigma N \leftrightarrow NN, \Lambda\Lambda \leftrightarrow \Lambda N \tag{6}$$

can create (destroy) the missing (abundant) strangeness content in the unstable regions. This task is forbidden for the strong interactions, due to the strangeness conservation. From the above discussion, it is clear that the hyperons are major components of the NS matter. A precise knowledge of their properties (hyperon-nucleus, hyperon-nucleon and hyperon-hyperon interactions and non-mesonic weak decays) is strongly necessary for their description. In the previous paragraph, it has been shown how PANDA can contribute to obtain the missing information in this field.

HADRON SPECTROSCOPY AND NUCLEON FORM FACTORS

The high performance of the HESR can also be used to shed light in the field of the hadron spectroscopy, in the charmonium and open-charm energy range. As a first observation, all charmed meson-antimeson states and most of the strange-charmed pairs are easily accessible at the HESR where theory also predicts hybrids, glueballs and other multi-quark states [6].

The nowadays known hadrons are color singlet systems, formed by $q-\overline{q}$, $q-q-q$ and $\overline{q}-\overline{q}-\overline{q}$ (where q and $\overline{q}$ indicate a quark and an anti-quark, respectively) but the QCD theory does not forbid the existence of other color singlet ”exotic” combinations.

Such exotic systems have been searched in the low energy range, below 2 GeV, mainly at LEAR in the 90-ties, but without any firm result [21]. The whole hadron spectrum, in addition to mesons, baryons and multi-quark states, also includes states with explicit gluon content, i.e. hybrids and glueballs. LQCD calculations show that in the range 1.5 - 5 GeV the predicted states are very close to each other in energy and sometimes they overlap [22]. Therefore, in order to distinguish between close states it is mandatory to make high precision measurements.

Concerning the state of art of the measurements, at present the hadron spectroscopy experiments do not see many of the predicted states while others, which do not fit the expectations, have been observed. The electron-positron collider's experiments (i.e. Belle2, BESIII) have discovered candidates for exotic states, but they are limited to low spin states [23]. The other present running facility, the LHC, is studying the hadron spectroscopy at very high energy. In this panorama, the features of the HESR antiproton facility can play a major role in getting complementary (or unique) information about these systems. In fact, the antiproton beam allows the direct formation of several charmonium states from the $\overline{p}-p$ initial state. On the other hand, the e^+e^- colliders only allow the formation of 1^{--} states, while the other states are produced from their decays: this process, in general, worsens the mass resolution. In the formation reaction, the profile of a resonance can be obtained by scanning the energy region across the resonance. Higher is the number of separated points in which the formation rate is measured, closer is the measured resonance profile to the real one. The measured rate $\nu(E)$ of the formed resonance at a certain energy E is proportional to the luminosity L_0 through the formula:

$$\nu(E) = L_0 \cdot \{\sigma_B + \epsilon \cdot \int_0^{\Delta E} \sigma_R \cdot f(E, \Delta E) \cdot dE\} \tag{7}$$

where ϵ is the overall detector efficiency, ΔE is the width of the energy distribution function $f(E, \Delta E)$, σ_R is the resonance cross section (typically a Breit-Wigner) and σ_B is the background cross-section. Equation 7 shows that a very small ΔE allows a dense scanning in the energy range of the resonance, but a statistically meaningful counting rate requires high luminosity to compensate the small value of the integral.

As mentioned in the Introduction, the antiproton beam of the HESR has both high resolution and intensity, to improve the quality of the present results. As a test, the PANDA Collaboration analyzed the case of the X(3872) state, whose nature is not yet definitely understood.

The X(3872) state has been discovered in 2003 by Belle and then seen by CDF, D0, BaBar, LHC experiments, in several decay channels. The mass (3871.69 0.17) MeV/c^2 [24] is known with a precision better than 1 MeV/c^2 but for the width only an upper limit, 1.2 MeV/c^2 at 90% C.L., is available. Different interpretations have been proposed for this resonance: charmonium state, $\overline{D_0^*}D_0$ molecule, tetra-quark state. Under realistic assumption for mass, width and formation cross section, the Monte Carlo simulations obtained mass resolution ≈ 5 KeV/c^2 and width precision ≈

10÷20% [25]. With these values, the width of X(3872) (and practically for all resonances in the charmonium energy range) will be precisely measured.

Another topic of the PANDA physics program is the study of the nucleon's structure. Nucleon Form Factors can be measured in the space-like region through scattering and in the time-like region through the reactions:

$$e^+ + e^- \rightarrow \overline{p} + p \tag{8}$$

$$\overline{p} + p \rightarrow e^+ + e^- \tag{9}$$

The time-like region is more puzzling, due to the difficulty of measuring the phases of the complex time-like form factors (TLFF's) and to the impossibility of exploring the unphysical region below two proton masses [26]. At present the experimental efforts are directed to increase the precision and to extend the kinematic range of the 4-momentum transfer squared q^2 [27]. BABAR Collaboration reported new measurements of the generalized Form Factor in the q^2 region up to 35 GeV^2/c^2 [28, 29]. Thanks to the HESR performances, PANDA Collaboration can contribute to this kind of measurements in the region up to ≈ 22 GeV^2/c^2.

CONCLUSIONS

The future FAIR complex will provide beams of ions and antiprotons, with high-intensity and very good momentum resolution. The scientific program of the PANDA experiment aims to study fundamental aspects of hadronic physics investigating the properties of the Doubly Strange Systems and contributing to the spectroscopy in the charmonium and open-charm energy region. The study of the hadron structure via electromagnetic reactions is also in the scientific program.

The common tool for achieving these goals is the use of the antiprotons stored in the HESR ring, at FAIR.

The strangeness physics sector will take advantage mainly from the high intensity of the beam that will allow collecting a huge amount of data to overcome the lack of statistics of the present measurements.It is expected to obtain an amount of data much greater than the worldwide existing statistics, thus contributing to the understanding of many aspects of the YY interaction and of the hyperon weak decay. This improvement will be greatly useful in describing the core of the neutron stars, where the presence of hyperons and their interactions play a crucial role in explaining the mass and size properties. The very good resolution, together with the high luminosity achievable, will also allow performing very precise measurements of the mass and width of all charmonium and open-charm states, and to study the nature of those that at present are poorly known. Finally, a contribution to the measurements of the time-like proton form factors in the range 5 - 22 GeV^2/c^2 will be possible.

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