Review of the scientific program proposed by the PANDA Collaboration

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I. THE EXPERIMENT AND ITS SCIENTIFIC GOALS

The PANDA Experiment (antiProton ANnihilations at DArmstadt) is under construction at the Facility for Antiproton and Ion Research (FAIR) at the GSI laboratory in Darmstadt, Germany. The experiment uses antiprotons produced by a primary proton beam and stored in the High Energy Storage Ring (HESR), interacting with protons and nuclei in a fixed target inside the PANDA Detector. The momentum range is between 1.5 and 15 GeV.

The Physics program deals with the most fundamental aspects of Quantum Chromodynamis (QCD) and mainly focuses on the following topics:

- Hadron spectroscopy. This item includes the search for multiquark states, open and hidden charm mesons, charmed and strange baryons, hybrids and glueballs.
- Hadron structure. This item includes the independent extraction of electric and magnetic nucleon form factors in the time-like region and the study of Drell-Yan lepton pairs at low transverse momentum.
- Physics of hypernuclei. This item includes the study of the spectrum and decay properties of double strange $\Lambda\Lambda$-hypernuclei.

The purpose of this document is to assess: i) the scientific interest of this program; ii) how well PANDA can do with respect to other existing or forthcoming experiments; iii) how much this program fits the physics interests of INFN.

II. HADRON SPECTROSCOPY

One of the main goals of the PANDA experiment is to investigate various aspects of hadron spectroscopy. Together with longstanding questions, such as the existence of glueballs and hybrids, there are a number of new states discovered since 2003 both in the open and hidden charm sector, which present puzzling features. A precise measurement of their masses and total widths, as well as of the lineshape in their exclusive decays, would shed light on the physical interpretation of these states.

PANDA could play an important role in this field using the method of the resonance scan which allows a great precision in the width measurements. Compared to previous experiments, PANDA performances are expected to be better, due to the larger instantaneous luminosity achievable, the better momentum resolution and the features of the detector. Moreover, in antiproton-proton annihilation, states can be formed directly with no limitation on their quantum numbers.

Hidden charm Mesons

Since 2003 the experimental study of charmonium-like X, Y, Z resonances has produced a large amount of information about their masses, widths and J^{PC} quantum numbers. There are several hints that most of these states cannot fit standard charmonium interpretations. Nevertheless, the experimental knowledge of this field has not yet proven to be sufficient to identify clear patterns pointing at a unified description of those resonances having most likely an exotic structure. Studying the features of X, Y, Z particles offers the concrete possibility to discover some new strong interaction dynamics which is suspected to be at work in their production and quark structure. The PANDA experiment is the only one guaranteeing the continuity in the exploration of this field which is necessarily in the stage of being experimentally driven.

Discovering that the $X(3872)$, the better known among X, Y, Z states, has a width $\Gamma \gtrsim 150$ keV (something beyond the capabilities of present experiments) would give a strong clue on the fact that it cannot be a $D\bar{D}^*$ loosely bound hadron molecule. Such a determination is within the reach of PANDA and would force to consider new ways of quark matter aggregation into hadrons. On the contrary, a smaller width would signal that strong interactions might have an unexpected behavior on length scales as large as 10 fm, leading to surprising achievements in this field: for example, Feshbach molecules, widely studied in the context of frontier atomic physics, could have analogues in the physics of hadrons.

The study of baryon-antibaryon modes is considered by many as a window on the search of multiquark structures. This has not been systematically pursued yet and is one of the opportunities offered by the PANDA experiment. The hadron-string picture, systematically developed in hadronization studies in high energy physics, predicts indeed a strong affinity of multiquark hadrons to decay into baryons. In turn, discovering multiquark states would force to reformulate our ideas about shower and hadronization mechanisms lying at the core of jet physics.

Due to the reduced background in radiative decays, the PANDA experiment may measure with unprecedented precision the ratio $R = \dfrac{\Gamma(X(3872) \to \psi(2S)\gamma)}{\Gamma(X(3872) \to J/\psi\gamma)}$, a quantity sensitive to the structure of the X.

Glueballs and Hybrids

QCD lattice simulations predict a number of glueball and hybrid configurations. If glueballs exist, they should decay to light flavours with the same probability, and their decays should evade the OZI rule. Glueball spectra have connections with many recent formal developments of non-perturbative QCD: one of the few fields in which string theory has shown to be able to provide testable predictions. The situation is similar for hybrids. One of the X, Y, Z, the $Y(4260)$, is a strong candidate to be an hybrid meson. The experimental difficulties in the search of these states are well known. PANDA has the capabilities to learn in this field at a high level of accuracy.

Open charm Mesons

Far from being established, the spectroscopy of open charm mesons has recently been enriched due to the recent discoveries of several new states. Among these, two new charmed-strange mesons, named $D_{sJ}(2317)$ and $D_{sJ}(2460)$ with spin-parity $J^P = 0^+$ and $J^P = 1^+$, respectively. They present intriguing features: their mass is below the $D\,K$ (for $D_{sJ}(2317)$) and $D^*\,K$ (for $D_{sJ}(2460)$) systems, so that they decay violating isospin. This would explain their observed narrowness, in contrast with the fact that they were predicted to be broad. The discovery of these states has prompted a number of theoretical analyses and a key point in understanding the correct interpretation of these states would be measuring their width, as well as measuring their radiative branching ratios. PANDA can help in both these goals and the same holds for a number of other open charmed mesons discovered afterwards, and still awaiting for the proper quantum number assignment.

III. HADRON STRUCTURE

$\bar{p}p$ annihilation into leptons

Studying $\bar{p}p$ annihilation into leptons ($\bar{p}p \to l^+l^-$), PANDA can access the electromagnetic form factors of the proton, G_E and G_M, in the time-like region. Among the existing and planned hadronic machines, PANDA will have the unique opportunity of combining the use of a nearly 4π detector with the capability of reaching an instantaneous luminosity of 10^{32} cm^{-2}sec^{-1} or higher. Therefore, PANDA is expected to improve the precision reached by the BaBar Collaboration in the measurement of the total cross section, by extending it also to very large $q^2 \sim 25$ GeV^2. The e^+e^- BEPC-II collider in Beijing is designed to reach a similar peak performance but only at the $\psi(3770)$ resonance, while the energy distribution of form factors is measured at a lower luminosity. Because of the almost-full angular coverage of its detector, PANDA should also be able for the first time to reliably disentangle the moduli of the two form factors up to $q^2 \lesssim 15$ GeV^2, with a statistical precision sufficient to discriminate among several model predictions that give similar results in the space-like region. Since the form factors in the time-like region are connected by analytical continuation to the space-like region, the knowledge of their q^2 behavior in the former region should shed light on the latter, where puzzling results emerge about the onset of perturbative QCD in the range $1 < Q^2 = -q^2 < 8$ GeV^2.

$\bar{p}p$ Drell-Yan production

PANDA will measure the production of Drell-Yan lepton pairs at invariant masses $1.5 \le M_{ll} \le 2.5$ GeV and with various transverse momenta q_T. In the range $q_T \ll M_{ll}$, a recently established QCD framework based on the so-called TMD factorization allows isolating in the hadronic tensor some soft universal functions named Transverse-Momentum Distributions (TMDs), or unintegrated parton distributions. The knowledge of these objects is crucial to parametrize the nonperturbative contribution of the q_T-dependent Drell-Yan cross section, and to match the predictions of QCD in collinear factorization at larger q_T. However, the knowledge of TMDs is currently very poor. PANDA will represent an important source of information on these quantities. In particular, being the only Drell-Yan experiment using antiprotons, PANDA will be particularly suited to study the (dominant) valence components of TMDs, including their flavor separation due to its capability of employing different hadronic targets. At PANDA, it will also be possible to study a specific TMD named Boer-Mulders function, which describes the correlation between transverse momentum and transverse polarization of quarks in an unpolarized hadron, and is directly related to the orbital motion of quarks. This partonic density is thought to be responsible of the observed large azimuthal $\cos 2\phi$ asymmetry in the unpolarized Drell-Yan cross section, which has not received yet a satisfactory explanation in the context of QCD collinear factorization.

IV. PHYSICS OF HYPERNUCLEI

At present, very few events of double strange hypernuclei have been detected. Except for the ${}^{6}_{\Lambda\Lambda}\mathrm{He}$ nucleus, their interpretation is not unique and no direct experimental information on possible excited states is available. At PANDA, double strange $\Lambda\Lambda$-hypernuclei will be formed in a three-step process starting from the creation of exotic hyperatoms via Ξ^- capture. The high luminosity of antiprotons accumulated in the HESR will allow to achieve much larger formation rates with respect to J-PARC, which is the only other facility providing data for double strange hypernuclei using a very different set-up.

Measuring the spectra and decay properties of double $\Lambda\Lambda$-hypernuclei will contribute in deepening our knowledge of the hyperon-hyperon interaction with several potentially important consequences. The comparison between single and double hypernuclei can give valuable information on the strangeness-nonconserving four-baryon interaction. The hyperon induced non-mesonic weak decays provide a unique access to the exotic $\Lambda\Lambda K$ and $\Lambda\Sigma K$ vertices giving new constraints on chiral perturbation theory in the weak SU(3) sector. Moreover, binding energies of double $\Lambda\Lambda$-hypernuclei provide upper limits for the one of the largely debated H-dibaryon, whose recently claimed evidence on the lattice does not correspond to convincing experimental signals.

Hypernuclear data provide valuable input to nuclear astrophysics as well. The hyperon-nucleon and hyperon-hyperon couplings give important information about the emergence of hyperons in the core of neutron stars and in the cooling behaviour of massive neutron stars. Non-mesonic weak decays of hyperons in a dense medium control the bulk viscosity of neutron star matter regulating the r-modes instability of pulsars and their emission of gravitational waves. In addition, a new class of hyperon stars can be formed if the hyperon-hyperon potential is found to be suitably attractive. Finally, hypernuclear physics can play a crucial role also in the core-collapse supernovae: the presence of a finite amount of strangeness, due to thermal formation of hyperons in supernova matter, can trigger a phase transition to quark matter which can be read off from the spectrum of (anti)neutrinos emitted from a galactic supernova.

V. CONCLUSIONS

From the short overview given in the previous sections, we can deduce that:

i) the PANDA physics program is at the forefront of the most updated research in Hadronic Physics, and some achievable results might have far-reaching consequences in the field of Strong Interactions; the scientific interest in this program from the community of Hadronic Physics is presently very high and lively,

ii) the performance of the designed machine is expected to be overall competitive with present and forthcoming similar facilities; in some aspects, PANDA has unique features that should allow to obtain unprecedented results setting a new standard in the corresponding research subfield,

iii) the PANDA physics program perfectly fits the interests of INFN, specifically of CSN3 and of those theoretical projects in CSN4 belonging to the Hadronic and Nuclear Physics research line.