

## FAIR PERSPECTIVES FOR HADRON PHYSICS\*

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The FAIR facility in Darmstadt has a broad program in the field of hadron and nuclear physics utilizing ion beams with unprecedented intensity and accuracy. The PANDA experiment, which is integrated in the HESR storage ring for antiprotons, is at the center of the hadron physics program. One of the main topics is hadron spectroscopy in the charmonium mass region where completely new phenomena in terms of unexpected resonances have recently opened a window to gain a deeper understanding of QCD.

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**1. The FAIR Facility and PANDA**

FAIR (Facility for Antiproton and Ion Research) was established as an international company on October 4<sup>th</sup>, 2010. It is set-up next to the existing GSI facility in Darmstadt, Germany. FAIR has a broad research program in hadron physics, nuclear structure physics, heavy-ion physics and atomic and plasma physics.

Hadron physics will mainly be done with antiprotons at FAIR. 30 GeV protons from the SIS100 are used to produce antiprotons that are subsequently collected, stored and cooled in two smaller storage rings. Those pre-cooled antiprotons are then transferred via the SIS100 into a dedicated antiproton storage ring called HESR. The HESR is equipped with one internal target station. The HESR will provide antiprotons with momenta between 1.5 and 15 GeV/c, and stochastic and electron cooling allow for a very small momentum spread of  $\Delta p/p \sim 10^{-4}$ – $10^{-5}$ .

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The PANDA experiment is designed to explore a broad physics program utilizing the cooled antiproton beams of the HESR with momenta up to 15 GeV/ $c$ :

- the study of gluonic degrees of freedom, *e.g.*, hybrids and glueballs,
- spectroscopy of states containing charm quarks.

Other physics topics not mentioned in the paper include:

- the study of the nucleon structure investigated in electromagnetic processes,
- spectroscopy of hypernuclei and double hypernuclei.

The construction of the FAIR site has started and a commissioning of the HESR is foreseen for the year 2018.

## 2. Gluonic degrees of freedom

Hadron spectroscopy is the basis that inspired the SU(3) quark model and QCD as the generally accepted theory of strong interactions. QCD is a non-Abelian gauge theory and, as a consequence, the gauge bosons, the gluons, can interact with each other. Therefore, QCD predicts the existence of bound states of gluons, called glueballs ( $gg$ ,  $ggg$ ). Other types of hadronic matter in which gluons contribute to the overall quantum numbers, called hybrids ( $\bar{q}qg$ ), could also exist. The gluonic excitation in a hybrid leads to new  $J^{PC}$  quantum numbers for this state, where  $J$  denotes the total angular momentum of the resonance,  $P$  its parity and  $C$  its charge conjugation. Some  $J^{PC}$  combinations cannot be formed by the fermion–antifermion  $\bar{q}q$  system, so their observation would be the cleanest experimental evidence for a non- $\bar{q}q$  state. In any case, the precise measurement of the properties of several glueball or hybrid states compared to  $\bar{q}q$  mesons would help us to understand QCD in the non-perturbative regime. Even though glueballs have been mentioned in the literature for a long time, their nature is completely unknown. It is *e.g.* not clear how much perturbative gluons play a role or if the structure of a glueball is a closed flux of color with twists and knots in it [1].

Why is it so important to find the gluonic degrees of freedom? The elementary particles of the Standard Model gain their mass through the Higgs mechanism. However, only a few percent of the mass of the proton is due to the Higgs mechanism. The rest is created in an unknown way by the strong interaction. Glueballs would be massless without the strong interaction and their predicted masses arise solely from the strong interaction. The possibility to study a whole spectrum of glueballs might, therefore, be the key

to understanding the mass creation by the strong interaction. What are the results in this field so far? Several reactions are considered to be gluon-rich. The most prominent are radiative  $J/\Psi$  decays, central production processes, and antiproton–proton annihilation. Because of the existence of LEAR at CERN, antinucleon–nucleon ( $N\bar{N}$ ) annihilation data now dominate.

The study of  $\bar{p}p$  annihilation has been underway for the past thirty years. Several bubble chamber experiments at CERN and BNL first investigated this topic. In 1983, with the low energy antiproton ring (LEAR) at CERN, a unique facility for antiproton physics came into operation. Until its closure at the end of 1996, LEAR provided pure and high-intensity antiproton beams ( $2 \times 10^6 \bar{p}/s$ ) in the momentum range between 60 and 1940 MeV/ $c$  with a small momentum spread of  $\Delta p/p \sim 10^{-3}$ . The second generation of LEAR experiments were comprised of high-statistics  $4\pi$  experiments for charged and neutral particles. This turned out to be the key to finding gluonic degrees of freedom. Not only was the most promising glueball ground-state candidate ( $J^{PC} = 0^{++}$ ), the  $f_0(1500)$ , discovered in  $\bar{p}p$  annihilations [2], but also two states with exotic quantum numbers ( $J^{PC} = 1^{-+}$ ) are unambiguously seen [3–5]. Because their quantum numbers are exotic, those two particles cannot be ordinary mesons. What is especially striking in  $\bar{p}p$  annihilations is the fact that these exotic particles are produced with the same strength as ordinary mesons. It, therefore, seems that the gluon richness of the annihilation process makes  $\bar{p}p$  annihilations the prime search ground for gluonic excitations. Unfortunately, the energy range of the LEAR machine was limited and, therefore, *e.g.*, higher-mass glueballs were out of reach. The majority of them are predicted by lattice calculations to have a mass between 3 and 5 GeV/ $c^2$  [6]. Because of this high mass, most of them are not accessible for radiative  $J/\Psi$  decays and central-production processes, and a new antiproton machine seems to be the only chance to find them and study their properties.

One new, recently discovered state is especially interesting in the context of glueball searches: the  $Y(4140)$ , which was discovered by the CDF Collaboration in the decay of  $B$  mesons. In the  $B^+ \rightarrow J/\Psi\phi K^+$  decay, evidence ( $3.8\sigma$ ) for a narrow  $J/\Psi\phi$  structure was reported in 2009 [7]. The signal was based on an integrated luminosity of  $2.7 \text{ fb}^{-1}$ . Further analysis with higher statistics ( $6.0 \text{ fb}^{-1}$ ) confirmed the early result [8], which now has a significance of more than  $5\sigma$ .

The mass and width given for the  $Y(4140)$  are:

$$M = 4143.4_{-3.0}^{+2.9} (\text{stat}) \pm 0.6 (\text{syst}) \text{ MeV},$$

$$\Gamma = 15.3_{-6.1}^{+10.4} (\text{stat}) \pm 2.5 (\text{syst}) \text{ MeV}.$$

The decay width of 15.3 MeV points to a strong rather than an electromagnetic or weak decay, but is nevertheless much narrower than most strong decays — this is reminiscent of the situation with the  $f_0(1500)$  and  $f_0(1710)$  in the light-quark sector. It was pointed out by the CDF Collaboration that the  $Y(4140)$  lies well above the open charm threshold; so if it were a normal charmonium state, it would decay predominantly into open charm pairs [7]. What is very intriguing about this state is that it is the first particle found to decay into two heavy quarkonia ( $c\bar{c}$  and  $s\bar{s}$ ), which looks exactly like a flavor-blind decay as is expected for glueballs. The  $Y(4140)$  is unlikely to be a  $J/\Psi\phi$  resonance since no such resonance is predicted to exist, and in mass it seems too far away from the threshold to be considered a molecule. What speaks against the  $Y(4140)$  being a glueball is that  $B$  decays are generally not considered to be gluon-rich. On the other hand, it is certainly worth noting that the BELLE Collaboration has searched for the  $Y(4140)$  in  $\gamma\gamma$  collisions but has not found it [9], and this non-detection is what one would expect from a glueball candidate. In order to make progress in understanding the  $Y(4140)$ , it would be necessary to establish other possible decay modes and determine its properties in detail. Since for statistical reasons this is possible neither in CDF nor at the  $B$  factories, only the PANDA experiment will have the possibility to do so in the foreseeable future.

PANDA should also be able to measure all glueballs below 5.4 GeV. The gluon-rich annihilation process has no restrictions on the quantum numbers of states that can be reached; this is in contrast to  $e^+e^-$  colliders, where only  $J^{PC} = 1^{--}$  can be produced and where all other states are seen solely in the decay chain of the vector state. Thus PANDA will be the only experiment to be able to do systematic studies of supposed glueball states, revealing their true nature and, hopefully, also giving insights into their structure. This structure is completely unknown and spectroscopy experiments may indeed be the only tool to reveal it. The vast majority of glueballs appear at masses overlapping with the charmonium spectrum. Therefore, lesser mixing with conventional mesons is expected in the charmonium mass region and glueballs may indeed be rather narrow states. The knowledge thus gained by understanding massless gauge-boson–gauge-boson interaction in form of glueballs in strong interactions might spill over to other fields and could *e.g.* influence developments of models of gravitation, where graviton–graviton interactions could be important.

A few years ago, the region above the open-charm threshold was mainly “terra incognita”. Very few resonances were known from  $e^+e^-$  colliders and resonances were expected to be mainly broad since their decay into open charm is feasible. Consequently, it came as a big surprise when mainly the BELLE and BaBar experiments at the  $B$ -factories discovered several states not fitting into the pattern. Nowadays they are referred to as  $X$ ,  $Y$ ,  $Z$  states.

In most cases, these states are associated with charmonium since the decay products contain charm quarks but their classification is far from being obvious. It is unexplained why, despite being above the open charm threshold, the strong decay mechanism into open charm is suppressed and the states decay rather into a charmonium ground state and light mesons. If some of them were hybrids, this could be an indication of the long lifetime and small width of gluonic excitations. The  $Z^+$  particles [10] must be multi-quark states containing two lighter quarks together with the charm–anticharm quarks, so undoubtedly new degrees of freedom in the strong interaction have started to show. The nature of most of the states is in most cases ambiguous and needs clarification in future experiments. They could *e.g.* be regular charmonia, multi-quark states, molecules, hybrids or glueballs. However, the possibility that both, multi-quark states and molecule-like states, might have appeared indicates that the charmonium mass region could be the one where the transition between colored strong interaction and colorless strong interaction would be studied best.

Current experiments cannot add much more information because the observed particles are produced in a decay chain and the knowledge of their properties is largely limited by detector resolution. Where tested, these states couple strongly to antiproton–proton annihilations as results from LEAR experiments but also from high-energy Fermilab experiments show. In most cases, a limited detector resolution will not be an issue at FAIR due to the possibility to directly scan the resonances with a high-precision antiproton beam allowing PANDA to clarify the nature of the  $X$ ,  $Y$  and  $Z$  states.

The appearance of additional narrow states in the charmonium mass region confirms the assumption that the identification of additional states is easier than in the light-quark sector due to reduced mixing. Mixing with conventional mesons is not at all an issue for hybrids with exotic quantum numbers, *i.e.* quantum numbers that could not be accommodated by a quark–antiquark pair. Several of the lowest-mass charmonium hybrids are predicted to have exotic quantum numbers. While usually the process of a complicated partial wave analysis leaves some ambiguities concerning the identification of an exotic nature, it can be easily established in antiproton–proton annihilations. In a production experiment, where the particle is usually produced together with a light meson, exotic quantum numbers are allowed for the unknown state. A subsequent formation experiment, with the center-of-mass energy of the experiment being exactly the particle mass should then allow to scan its properties. The exceptions are particles with exotic quantum numbers which cannot be reached in a formation experiment. Therefore, the appearance of a resonance in a production experiment and its absence in a subsequent scan shows immediately its exotic nature.

The performance of the PANDA detector to detect these states has been carefully studied, *e.g.* in the case of the  $Y(3940)$ , which has been seen only in the unusual decay mode into  $J/\Psi + \omega$  [11]. Figure 1 (left) shows the Monte Carlo simulation of the signal in PANDA, which is very clean. Background suppression on the level of better than  $10^8$  works superb by using the signal from the high-energetic electrons in the decay of the  $J/\Psi$  (Fig. 1 (right)).

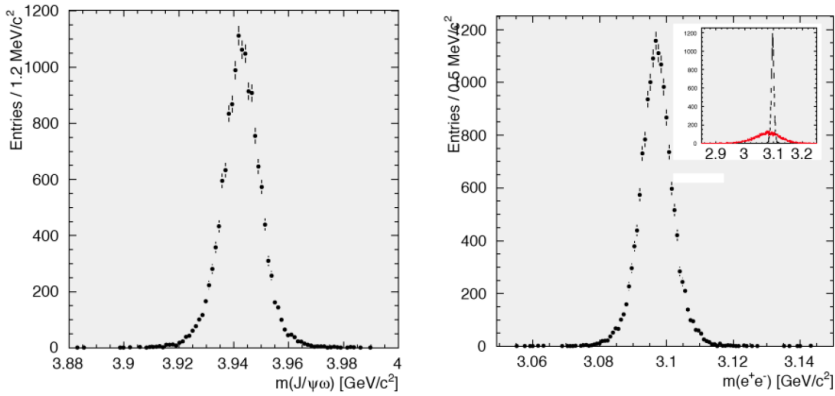


Fig. 1. Left: the invariant  $J/\Psi\omega$  mass distribution obtained in PANDA MC studies; right: the invariant  $e^+e^-$  mass spectrum before (inset) and after kinematic fitting.

An excellent electromagnetic calorimeter, as the one foreseen for PANDA, is mandatory for such measurements.

### 3. The PANDA Detector

Most of the experimental program will be done with a general-purpose detector [12], which is currently being designed by the PANDA Collaboration consisting of 56 institutions worldwide.

To achieve the physics aims, the detector needs to cover the full solid angle. Good particle identification and excellent energy and angular resolution for charged particles and photons are mandatory. Charm particles decays often lead to di-lepton pairs. Thus, muon detection capabilities and a highly-segmented low-threshold electromagnetic calorimeter are important to tag and precisely reconstruct hidden-charm and to reduce background. Good vertex recognition and particle identification for charged kaons from very low energies up to a few GeV are required to reconstruct light hadronic and open-charm final states. At the same time, the detector must withstand large radiation dosage from hadrons emitted by the spallation process when using nuclear targets. These spallation products include neutrons down to thermal energies, which contribute most.

The planned PANDA detector is subdivided into two parts: (i) a target spectrometer with a solenoid magnet surrounding the interaction region and (ii) a forward spectrometer with a large-acceptance dipole magnet. The dipole magnet in forward direction bends as well the HESR beam, allowing for an electromagnetic calorimeter to be placed in  $0^\circ$  direction. Only this combination of two spectrometers, therefore, allows a full angular coverage and takes into account the wide range of energies. At the same time, it still has sufficient flexibility, so that individual components can be exchanged or added for specific experiments, *e.g.* for the experiments with hypernuclei or for the special needs of CP violation studies.

The internal target, which could be a pellet target of frozen hydrogen droplets, a gas jet target or a wire used as nuclear target, is surrounded by Si-pixel detectors in the vertex region. The main vertex tracking further out is done with a straw chambers and GEM-based trackers. Ring imaging Cherenkov counters will provide the particle identification. The proposed electromagnetic calorimeter is an arrangement of  $\text{PbWO}_4$  crystals of the newest generation of this material, read out by avalanche photodiodes and vacuum phototriodes or tetrodes. The superconducting solenoid provides a field of 2 T. Particles emitted with polar angles below  $10^\circ$  in the horizontal and  $5^\circ$  in the vertical direction are measured with the help of a 1 m gap dipole. Mini drift chambers will be located before and behind the dipole for tracking. Particle identification will be obtained by a TOF-Stop detector and a dual-radiator RICH detector. Behind this, there is a shashlyk electromagnetic calorimeter and a hadronic calorimeter followed by a muon detection system.

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