The CLAS12-PANDA Spectroscopy Program

Understanding the hadron spectrum is one of the fundamental issues in modern particle physics. We know that existing hadron configurations include baryons, made of three quarks, and mesons, made of quark-antiquark pairs. However we also know that most of the hadron mass is not due to the mass of these elementary constituents but to the force that binds them. Studying the hadron spectrum is therefore a tool to explore one of the fundamental forces in nature, the strong force, and Quantum Chromo Dynamics (QCD), the theory that describes it. This investigation can provide an answer to fundamental questions as what is the origin of the mass of hadrons, what is the origin of quark confinement, what are the relevant degrees of freedom to describe these complex systems and how the transition between the elementary constituents, quarks and gluons, and baryons and mesons occurs.

# Hadron Spectroscopy and study of QCD bound states at CLAS12

Hadron spectroscopy and, in general, the study of the properties of QCD bound states represents an important part of the physics program of the CLAS12 experiment at Jefferson Lab. The experiment will exploit the high duty cycle, high polarization electron beam provided by the CEBAF accelerator to study exclusive final states and investigate the production and decay of hadron resonances. Given the maximum electron beam energy of 11 GeV, a center-of mass energy above 4 GeV can be reached on proton targets, allowing scientists to study baryon resonances produced in the s channel up to masses of the order of 3.5 GeV and meson resonances of mass up to 2.5 GeV. The experiment will run at a luminosity of 1035cm-2s-1, giving access to process with cross sections down to the order of nbarns, in limited amount of time. Using polarized electron beam and polarized targets, polarization observables will be measured in addition to cross sections and decay angular distributions. The scattering of the primary electron beam on proton targets will be used to investigate electro-production processes from small to large momentum transfer Q2, studying the evolution of QCD dynamics. Quasi-real photo-production, occurring when the primary electron is scattered at very small angles, will be used to study the baryon and meson spectrum investigating properties of known resonances and searching for new and exotic states. Thanks to the excellent particle identification capabilities of the CLAS12 detector, multi-particle final states with both neutral and charged particles, including kaons, will become accessible, launching a comprehensive program of hadron spectroscopy in the light-quark sector.

## Physics Program

* **Meson Spectroscopy.** Mesons, being made by a quark and an antiquark, are the simplest quark bound system and therefore the ideal benchmark to study the interaction between quarks and understand what the role of gluons is. In this investigation, it is fundamental to precisely determine the spectrum and properties of mesons but also to search for possible unconventional states beyond the quark-antiquark configuration as tetraquarks (), hybrids () and glueballs. The meson spectroscopy program of the CLAS12 experiment includes, in fact, the following topics:
	+ **Hybrid mesons and exotics.** For many years, there have been speculations on the existence of hybrid mesons () and other resonances beyond those predicted by the quark model. The existence of these states and predictions for masses and decay widths have been based on various models and recently confirmed by first principle computations using lattice gauge. CLAS12 will search for these states by performing full partial wave analysis of several final states, focusing on the mass range of 1.5-2.5 GeV. Final states such as 3π or πη, where evidence of exotic signals was reported by previous experiments, will be investigated to provide confirming evidence, while strangeness-rich final states, such as φπ, will be studied searching for evidence of exotics with hidden strangeness. This research program will utilize quasi-real photo-production on proton target, exploiting the linear polarization of the virtual photon to simplify and constraint the partial wave analyses.
	+ **Study of scalar mesons.** Scalars with *JPC* = 0++ are some of the most intriguing bound states in QCD. They have in fact the same quantum number of the QCD vacuum and the lowest mass state, the so-called *f*0(600) or σ, is the field that in the non-linear σ model breaks chiral symmetry giving mass to the Goldstone bosons of QCD. The scalar sector presents however some of the most intriguing puzzles because, even if several states have been identified, the interpretation of their structure in terms of constituents is still quite unclear and assignments in the quark model classification are at most tentative. Open questions arise both from the unusual mass hierarchy of the lightest scalar nonet, formed by the σ, κ, a0(980), f0(980), and from an excess of I=0 state in the 1-2 GeV mass range. This excess has lead to speculations about the real nature of these states and the possible presence of an unconventional state, a glueball or a tetraquark. Testing these hypotheses and determining the inner strcture of these resonances requires high precision data for the scalar wave amplitude to allow an accurate extraction of the resonance poles. This will be performed by CLAS12, focusing on the first scalar nonet and other states with masses up to 2.0-2.5 GeV.
	+ **Strangeonia**. Presently available data on the strangeonium spectrum, i.e. states containing a pair, are rather sparse. Conventional strangeonia are in the constituent quark model radial and orbital excitation of the ground state φ(1020). Masses are expected to be between 1 and 3 GeV but, so far, of the 22 predicted states only 5 have been observed. In addition to the conventional states, exotics are also expected. CLAS12 will search for both conventional and exotic strangeonia in final states such as charge and neutral KK and KK\*, φπ and φη. The latter will be particularly important since, according to the Zweig rule, the contribution of states is expected and interference with states should be highly suppressed: just the mere identification of a resonance in the φη system would therefore prove the presence of a  state.
* **Spectroscopy of Strange Baryons.** This sector is of particular interest in hadron spectroscopy because of the lack precise information on excited hyperons Almost half a century after the prediction and discovery of the Ω− baryon, many properties of the S = −2 and −3 hyperon resonances remain unknown and the number of states that have been clearly identified is much below the expectations based on the constituent quark model. The CLAS12 experiment offers a unique opportunity to study the production mechanism of these resonances baryons with high precision and statistics in exclusive photo-nuclear reactions. The experiment will focus on determining the production mechanisms of these states via the measurement of cross sections and polarization observables, and on searching for missing states. Of particular interest is the production mechanism of the Ω−, which is expected be quite specific, since it is the first baryon whose constituents cannot come from the target proton. In addition, the spin-parity of the few relatively well-established cascade states, such as Ξ(1690) and Ξ(1820), will be confirmed via the double moments analysis technique using the combined decay angular distributions.
* **Nucleon Resonance Studies.** Exclusive single-meson and double-pion electroproduction cross sections off proton target will be measured to study nucleon resonances with the CLAS12 detector and 11 GeV electron beam. Exclusive final states will be measured, including both charge and neutron particles, to study the production of nucleon resonances. Detecting the scattered electron and determining the four-momentum transfer, Q2, of the virtual photon it will be possible to explore the nature of the electro-excitation process for different wavelengths. From these measurements, the electromagnetic transition form factors for well established excited nucleon states will be extracted for the first time in an unexplored domain of Q2 from 5.0 to 10.0 GeV2. These will allow scientists to explore the evolution of the active degrees of freedom in excited nucleon states from meson-baryon dressing to dressed quark contributions, and to learn how the strong interaction creates dressed quark cores in various N∗ and how they emerge from QCD.

# Hadron Spectroscopy and study of QCD bound states at PANDA

The PANDA experiment at the High-Energy Storage Ring (HESR) at FAIR will study antiproton collisions with fixed target protons and nuclei up to beam momenta of 15 GeV/c (corresponding to a maximum center-of-mass energy of approximately 5.5 GeV). Antiproton-proton interactions offer a unique tool to perform high precision spectroscopy, because in these collisions all non-exotic states can be formed directly: this implies that the measurement of masses and widths is very accurate because it depends only on the beam parameters and is not limited by detector resolution. The antiproton beam from the HESR will be characterized by a beam momentum spread *δp/p* between 10-4 (in high-luminosity mode) and 10-5 (in high-resolution mode) allowing the measurement of sub-MeV widths. The maximum instantaneous luminosity will vary between 2×1032 and 1031 in the two modes, respectively, thus allowing the measurement of processes with very low cross sections (in the few pb range).

The physics program of PANDA addresses central issues of strong interactions. It consists of a wide variety of measurements, in which the spectroscopy of QCD bound states plays a central role.

## Physics Program

* **Spectroscopy of QCD bound states**. One key problem of QCD is to understand its spectrum. Most observed states can be understood as conventional mesons (quark-antiquark) or baryons (three quarks). However the theory also predicts glueballs, states made entirely of the QCD gauge bosons, and also more exotic forms of matter, like multiquark states, molecules or hybrids composed of quarks and gluons. There are some indications for the existence of such states in the light quark sector, but the overall picture remains puzzling. The important step is to identify exotic states in the heavy quark sector, where mixing of states is considerably smaller, predictions are more precise and therefore interpretations are less ambiguous. This field has experienced a true renaissance in the past few years due to the observation at BaBar, Belle, BES and CLEO of the so-called X, Y, Z states, whose interpretation in terms of conventional quark-antiquark pairs is unclear and whose nature remains unknown. These observations show that our understanding of QCD is in many respects only marginal and highlights the need for more refined and surgical experiments to eventually unravel the nature of these states and the true spectrum of QCD.

The measurements to be carried out by PANDA include the following:

* + Charmonium Spectroscopy. The charmonium spectrum can be calculated within the framework of non-relativistic potential models, EFT and LQCD. All 8 charmonium states below open charm threshold are known, but the measurements of their parameters and decays is far from complete (e.g. width and decay modes of hc and ηc(2S)). Above threshold very little is known: on one hand the expected D- and F- wave states have not been identified (with the possible exception of the ψ(3770), mostly 3D1), on the other hand the nature of the recently discovered X, Y, Z states is not known. At full luminosity PANDA will collect several thousand ‾cc states per day. By means of fine scans it will be possible to measure masses with an accuracy of the order of 100 KeV and widths to 10% or better. PANDA will explore the entire energy region below and above the open charm threshold, to find the missing D- and F- wave states and unravel the nature of the newly discovered X, Y, Z states.
	+ Search for gluonic excitations. The spectrum of hybrids and glueballs can be calculated within the framework of various models and recently, with increasing precision, in LQCD. Many of these states are predicted with JPC exotic quantum numbers, which represents a very clear experimental signature. PANDA will search for these states in the charmonium energy region: in production experiments only states with non-exotic quantum numbers, whereas only non exotic states can be obtained in formation.
	+ D-meson spectroscopy. The recent discoveries of new open charm mesons at the BaBar, Belle and CLEO has attracted much interest both in the theoretical and experimental community, since the new states do not fit well into the quark model predictions for heavy-light systems in contrast to the previously known D states. An important quantity which allows to distinguish between the possible different theoretical pictures is the decay width of these states (in particular the Ds states). So far only experimental upper limits of a few MeV exist, limited by the detector resolution. Thanks to the excellent definition of the HESR antiproton beam PANDA will be able to measure these widths down to values of ~100 KeV by measuring the production cross sections close to threshold, which is sensitive to the resonance width.
	+ Baryon spectroscopy. An understanding of the baryon spectrum is one of the primary goals of non-perturbative QCD. In the nucleon sector, where most of the experimental information is available, the agreement with quark model predictions is astonishingly small, and the situation is even worse in the strange baryon sector. The PANDA experiment is well suited for a comprehensive baryon spectroscopy program, in particular in the spectroscopy of (multi-)strange and possibly also charmed baryons.
* **Non-perturbative QCD dynamics**. In the quark picture hyperon pair production either involves the creation of a quark-antiquark pair or the knock out of such pairs out of the nucleon sea. Hence the creation mechanism of quark-antiquark pairs and their arrangement to hadrons can be studied by measuring the reactions of the type ‾pp →‾YY, where Y denotes a hyperon. By comparing several reactions involving different quark flavors the OZI rule and its possible violations can be tested for different levels of disconnected quark-line diagrams separately. Furthermore the parity violating weak decay of most ground state hyperons introduces an asymmetry of the decay particles and gives access to spin degrees of freedom for these processes. A systematic investigation of these reactions will bring new information on single and multiple strangeness production and its dependence on spin observables. The large amount of observables and high statistics PANDA data will allow for a partial wave analysis, making it possible to determine relevant quantum numbers, coupling constants and possibly find new resonances.

# Conclusions

The objectives of the CLAS12 and PANDA physics program for the study of QCD bound states present several commonalities and overlaps. As explained in the previous sections, the goals of the research planned by the two Collaborations coincide, being focused on understanding the structure of QCD bound states, determining the spectrum of mesons and baryons, searching for exotics and studying hadron production mechanisms. The methods followed by the two experiments, however, differ both for the energy and mass range that will be explored and for the probes that are being used. CLAS12 will focus on the light-quark sector while PANDA will dominantly investigate heavy flavor and charm, in particular.

In the meson sector, these characteristics lead to a very clear complementarity of the two experiments. CLAS12 will study the spectroscopy of light quark mesons, investigating also specific sectors such as scalar and strangeness-rich states. Phenomenological models and Lattice QCD calculations will provide the main theoretical guidance for the experiment. Using photo-production, CLAS12 is expected to provide important input in the search for hybrid mesons that are supposed to couple significantly to the photon probe. PANDA will study mainly the spectroscopy of charmonium and open charm. In this sector, theoretical guidance can arise not only from Lattice QCD calculations, but also from non-relativistic models and effective field theories that have been proven to describe successfully the charmonium spectrum. Based on the projected statistics, the experiment is expected to have a very strong impact in the field. In the search for exotic, proton-antiproton annihilation is expected to create a glue-rich environment, which should be well suited for the search for glueballs. In spite of these differences, the commonality of the final objectives makes the two programs deeply connected. Precise determination of light quark meson properties from CLAS12 will help constraining the decay of heavier mesons studied at PANDA. Any possible finding concerning exotics and unconventional mesons reported by one experiment will have a strong impact on the program conducted at the other facility. Ultimately, a tight collaboration between CLAS12 and PANDA will be beneficial for both collaborations and will strengthen their impact in the field of spectroscopy.

In the baryon sector, the overlap of the two physics programs is very strong. Study of the nucleon resonances and hyperon spectra and production mechanisms are the main goals of the research activity of both experiments. Given the high statistics and high precision expected both from CLAS12 and PANDA, significant progresses in the search for missing states and the determination of baryon properties are expected. The complementarity arising from the different reaction processes that will be studied would make a tight collaboration of the two experiments very productive.