

The meson spectroscopy program with CLAS12 at Jefferson Laboratory

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The study of the hadronic spectrum is one of the most powerful tools to investigate the mechanism at the basis of quark confinement within hadrons. A precise determination of the spectrum allows not only to assess the properties of the hadrons in their fundamental and excited states, but also to investigate the existence of states resulting from alternative configurations of quarks and gluons, such as the glue-balls, hybrid hadrons and many-quarks configurations.

The study of the mesonic part of the spectrum can play a central role in this investigation thanks to the strong signature that the hybrid mesons are expected to have: the presence of explicit gluonic degrees of freedom in such states may result in J^{PC} configurations not allowed for the standard $q\bar{q}$ states. From the experimental side the expected high-multiplicity decays of the hybrid mesons require an apparatus with high performances in terms of rate-capability, resolution and acceptance. The CLAS12 experiment (formally MesonEx) is one of new-generation experiments at Thomas Jefferson National Laboratory (JLAB) for which an unprecedented statistics of events, with fully reconstructed kinematics for large particle multiplicity decays, will be available. A wide scientific program that will start in 2016 has been deployed for meson spectrum investigation with the CLAS12 apparatus in Hall B at energies up to 11 GeV. One of the main parts of the program is based on the use of the Forward Tagger apparatus, which will allow CLAS12 experiment to extend the study of meson electro-production to the quasi-real photo-production kinematical region (very low Q^2), where the production of hybrid mesons is expected to be favoured. The data analysis which is required to extract the signal from hybrid states should go beyond the standard partial wave analysis techniques and a new analysis framework is being set up through the international network Haspect. The Haspect Network gathers people involved into theoretical and experimental hadronic physics all over the world, to investigate and propose new analysis models and new statistical techniques to unfold signal and background. The new analysis framework is being developed and tested using the existing CLAS data and results are projected to the CLAS12 performances, showing that the quest for hybrid exotic mesons is at reach.

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1. The meson spectrum and the hybrid configurations

The Hadron spectroscopy is a fundamental tool to explore the nature of matter, allowing to study the origin of baryons and mesons masses and of quark confinement.

The meson spectrum in particular may carry fundamental information about the gluonic contribution in the hadron structure thanks to the possible presence of states with explicit gluonic degrees of freedom. These hybrid states are characterized by J^{PC} configurations not allowed for standard $q\bar{q}$ states, so they represent a clear signature that can be experimentally investigated through Partial Wave Analysis (PWA) of the experimental data.

Several theoretical models include gluonic excitations contribution within different frameworks [1][2][3]: in this work the attention is focused on the Flux-tube model [4]. The gluonic flux tubes are a consequence of the non-abelianity of Quantum Chromo-Dynamics (QCD) theory, which, differently from Quantum Electro-Dynamics (QED), allows to the gauge bosons (the gluons) to interact among each other, forming flux tubes which bind the interacting quarks. In this model, standard meson configurations correspond to ground states of the flux tube and the possible quantum numbers are in agreement with the Gell-Mann model, whereas hybrid meson configurations correspond to flux-tube excited states ($J^{PC} = 1^{+-}$ or $J^{PC} = 1^{-+}$) where quantum numbers such as $J^{PC} = 0^{+-}, 1^{-+}, 2^{+-}$ are possible.

The flux-tube picture explains well also the hadronization process and the high particle multiplicity states in which a hybrid meson is supposed to decay in. A flux-tube binds two interacting quarks with a force of the form $\vec{F} = -k\vec{x}$, where k is a constant which is proportional to the strength of the interaction and \vec{x} is the distance between the two quarks. The binding potential $V = -\frac{1}{2}kx^2$ grows rapidly with $|\vec{x}|$, until it reaches at least the energy of the pion mass. At this point the breaking of the flux-tube may occur with the formation of at least two new mesons in which the mother particle has decayed in.

In this picture the hybrid mesons are supposed to decay in high-particle multiplicity events because the flux-tube binding the quarks is in an excited state, a condition that enhances the energy available to form couples of new mesons.

Hints about the existence of such hybrid states come from Lattice QCD (LQCD) with unquenched calculations, that in these last years is approaching a pion mass considerably close to the physical one [5]. According to these calculations, the lowest lying hybrid meson surprisingly presents the configuration $J^{PC} = 1^{-+}$ with a mass of about 1.6 GeV, followed by the configuration 0^{+-} with a mass of about 2 GeV. Both masses fall well in the mass range accessible to the CLAS12 experiment at the Thomas Jefferson National Laboratory (JLAB).

The experimental history about evidences of such hybrid states starts in the 80's, when a joint CERN-IHEP experiment (GAMS group [6]) claimed for a possible existence of hybrid state $J^{PC} = 1^{-+}$: in the analysis of the channel $\pi^- p \rightarrow \pi^0 \eta n$, a p-wave contribution of the $\eta\pi$ bound state (namely $\pi_1(1400)$) was supposed to exist to better explain the behavior of the experimental data. To confirm that claim, the experiment E852 at the Brookhaven National Laboratory [7] started a series of systematic studies of the same channel and the crossed-charged one ($\pi^- p \rightarrow \pi^- \eta p$) at 18 GeV, observing the lower lying hybrid state. Also the experiments Crystal Barrel [8] and VES [9] confirmed such observations, by studying the channels $n\bar{p} \rightarrow \pi^- \pi^0 \eta$, $p\bar{p} \rightarrow \pi^0 \pi^0 \eta$ and $\pi^- N \rightarrow \pi^- \eta N$ respectively.

Another possible candidate for the lowest lying hybrid state $J^{PC} = 1^{-+}$ is the $\pi_1(1600)$, whose experimental evidence has been more controversial. The E852 experiment at Brookhaven National Laboratory claimed for the existence of such excited state [10] analyzing a dataset of 250 thousand $\pi^- p \rightarrow \pi^- \pi^- \pi^+ p$ events at 18 GeV. In a following re-analysis of a higher statistical sample the previous claim was not confirmed [11], but recently the hybrid $\pi_1(1600)$ has been observed with high statistics by the COMPASS experiment in the $\pi P b \rightarrow \pi \pi \pi P b$ channel [12].

2. The CLAS12 apparatus at the CEBAF accelerator: the meson spectroscopy program and the experimental investigation of hybrid mesons

The experimental investigation of hybrid mesons will be one of the main tasks of the spectroscopy program of the CLAS12 (formally MesonEx) experiment, located on the experimental Hall B of the Jefferson Laboratory.

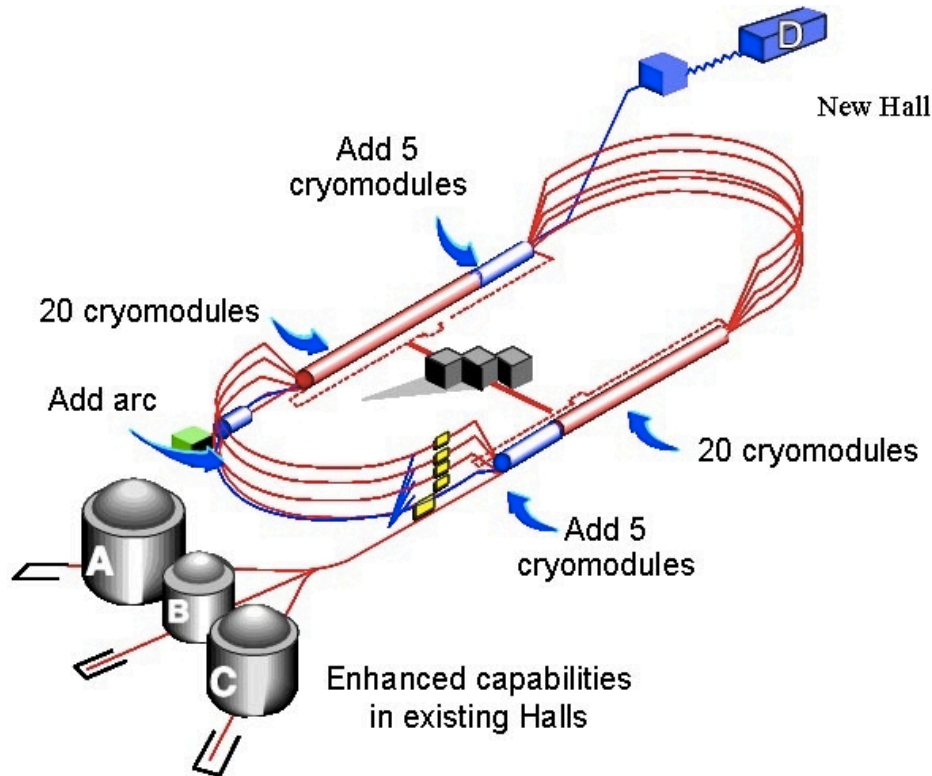


Figure 1: (Color online) Schematic view of the CEBAF accelerator at Jefferson Laboratory. The two linacs made of 25 cryo-modules each (in red and blue) are placed between two sets of five recirculating arcs each (in red). At the fifth pass the beam is extracted to the Hall B toward the CLAS12 apparatus with an energy of 11 GeV and an average accelerated current of $200 \mu A$. In the picture the Hall D is shown, where the GluEx experiment, also involved in the meson spectroscopy program of JLAB, is located.

The recent upgrade of the Continuous Electron Beam Accelerator Facility (CEBAF) to 12 GeV [13] will allow CLAS12 to investigate the mass range where the exotic states are supposed to lie. The accelerator is based on the Superconductive Radio-Frequency technology with two linacs,

made of 25 cryo-modules each, placed between two sets of recirculating arcs (see fig. 1): such configuration enhances the energy of the accelerated electron beam by 1.2 GeV at each round-pass. When the beam reaches an energy of 11 GeV (5th pass) it is extracted to the Hall B with a maximum delivered current of 200 μ A.

CLAS12 is the new experimental apparatus specifically designed for the upgraded CEBAF electron beam [14], that is replacing the former CLAS experiment, which took data until 2012. The geometry of the new apparatus ensures an acceptance which is close to 4π and a good hermeticity: the spectrometer is divided into 6 sectors corresponding to 6 different azimuthal regions, and it covers both the regions around the target (Central Detector region) and the forward direction region (Forward Detector region). The magnetic field, which is used to measure the particle momenta, is generated by a superconductive solenoid magnet (5 T) in the Central Detector and by a superconductive torus magnet (3.6 T) in the Forward Detector. The different detectors of the experimental apparatus are indicated in figure 2; they are described in detail in [14] and schematically in [15].

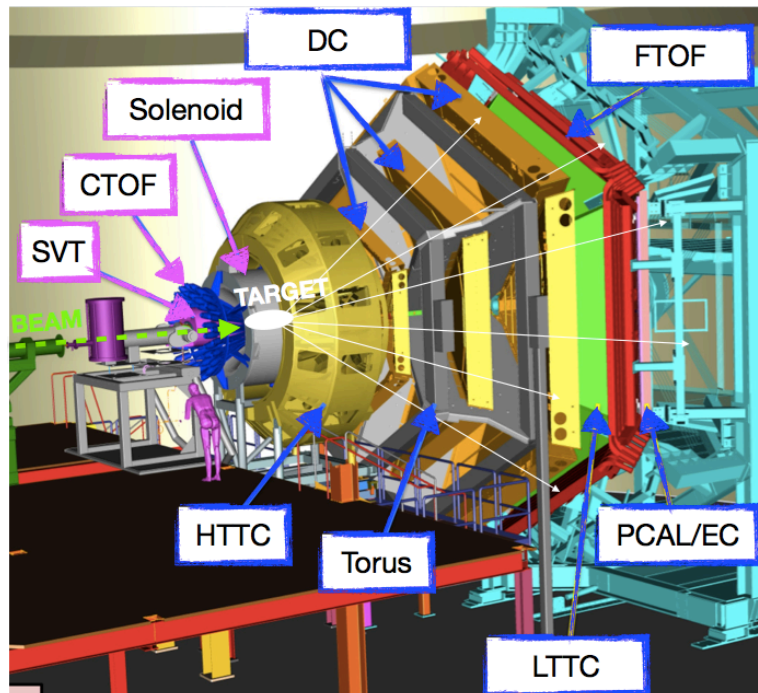


Figure 2: (Color online) The MesonEx apparatus: the dashed (green) arrow shows the incident beam on the target (in white). The parts of the Central Detector (highlighted in magenta) are: the Silicon Vertex Tracker (SVT), the Central Time of Flight system (CTOF) and the Solenoid. The parts of the Forward Detector (highlighted in blue) are: the High Threshold Cherenkov Counter (HTTC), the Lower Threshold Cherenkov Counter (LTTC), the Drift Chambers (DC), the Forward Time of Flight System (FTOF), the Pre-Shower Calorimeter (PCAL), the Electromagnetic Calorimeter (EC) and the Torus Magnet, whose six coils define the six separate regions, which compose the apparatus.

In the large meson spectroscopy program of the CLAS12 experiment, the investigation for such hybrid states will be deployed in the mass range which goes from 1 to 3 GeV, using photo-production reactions. The production of exotic hybrid mesons is expected indeed to be favored using a photon beam rather than a meson beam (K or π), because of the different final J^{PC} configurations accessible by a $J = 1$ probe (the photon) interacting with a nucleon. In particular, arranging the first excited states of the flux-tube ($J^{PC} = 1^{+-}$ or $J^{PC} = 1^{-+}$) with the $J = 1$ number carried by the photon, it is possible to form several hybrid exotic J^{PC} configurations not directly accessible via a meson-probe with $J = 0$. Moreover the linear polarization of photons may be used to filter out background contributions and distinguish unnatural parity exchange terms (proper of the hybrid meson production) from the natural ones, expected for the standard mesons [16].

3. Photoproduction reactions in Hall B

The Hall B at Jefferson Lab has a longstanding experience about photoproduction reactions and experimental techniques used to produce a photon beam. During the 6 GeV era, for the CLAS experiment, the bremsstrahlung emission was used to produce a tagged real γ -ray beam [17]. The electron beam may impinge on a thin diamond radiator to produce linear polarized photons. The electron and the photon beams are separated passing through the dipole of the tagger apparatus, which bends the electrons on a scintillating *hodoscope*. Nowadays this techniques is used to produce the photon beam for the GlueX experiment in Hall D at Jefferson Laboratory, which, as the CLAS12 experiment, has an important meson spectroscopy program.

In the 12 GeV era a different technique will be used for the CLAS12 experiment to study photo-induced reactions: the quasi-real photoproduction. Such technique is quite well established in higher energy physics experiments like HERMES, BABAR [18] and COMPASS [12], and it will be used for the MesonEx to search for the hybrid meson states with a complementary approach to the GluEx experiment. The quasi-real photoproduction technique takes place in the electroproduction regime: when the electron beam impinges on the nuclear target, the electrons are scattered by an angle θ . Events with a small θ are the ones where the exchanged photon between the probe and the nucleon of the target has a low Q^2 or, in other words, the γ is quasi- on mass shell. Such events correspond to quasi-real photoproduction.

In CLAS12 experiments the electrons, scattered at small θ angles, are detected by the Forward Tagger (see Fig.3), an apparatus placed after the nuclear target (in the forward direction), which covers a θ range from 2.5 and 4.4 degrees. The apparatus is composed by a tracker, based on Micromegas technology, to measure the angle θ and the polarization plane; a scintillation hodoscope, used as a veto for gammas, and an electromagnetic calorimeter made of $PbWO_4$ crystals, to measure the scattered electron energy. In a photoproduction event, tagged by the Forward Tagger, the multi-particle hadronic decay is detected by the CLAS12 apparatus, which provides a high rate capability, almost a 4π acceptance and excellent PID. Quasi-real photons will have an energy spectrum between 6.5 and 10.5 GeV, a linear polarization degree that can be up to the 70% of the electron beam polarization and a high luminosity, of the order of $10^{35} \text{ cm}^{-2}\text{s}^{-1}$ (considering 5cm long LH_2 target).

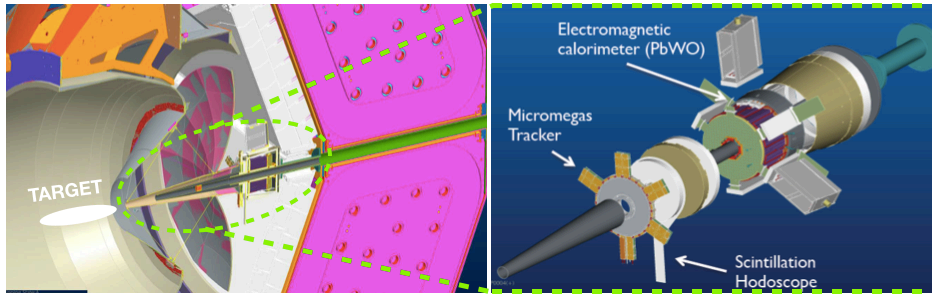


Figure 3: (Color online) Left panel: the Forward Tagger apparatus is located behind the nuclear target (in white). Right panel: sketch of the Forward Tagger where different parts and detectors are visible. In particular the Møller cone, designed to absorb the Møller electron scattered from the target is shown; it is followed by the Micromegas tracker, the scintillation hodoscope and the electromagnetic calorimeter with $PbWO_4$ crystals.

4. PWA and the establishment of a common analysis framework: the HASPECT network

As introduced in the previous sections a hybrid meson contribution is characterized by a well defined angular momentum state, so the Partial Wave Analysis is the fundamental tool to disentangle the small contribution of an exotic state among the experimental data. In the PWA the cross section is parametrized as the sum of partial amplitudes, each one related to a defined angular momentum contribution and described by a mathematical model, such as the isobar model or the dispersion relations.

In order to perform the partial wave analysis it is crucial that the experimental apparatus, with its acceptance and resolution, doesn't distort the reaction mechanism which may hide the hybrid contribution. This experimental problem has been investigated for the CLAS12 experiment using two complementary approaches. A first feasibility test has been done using simulated data for the $\gamma p \rightarrow \pi^+ \pi^+ \pi^- n$ channel where the sum of 8 isobar channels has been considered to describe resonances in S, P, D and F waves decaying into $\rho\pi$ or $f_2(1270)$. In these data an exotic contribution in the P wave has been injected to simulate the hybrid $\pi_1(1600)$ decaying in ρp , with a cross section of 200 nb. After folding the events with the CLAS12 acceptance and processing them through the full reconstruction chain, the data have been fitted using a proper partial wave set in the framework of the isobar model, in selected bins of transferred momentum t . The obtained results, in two t bins marked by points of different colors, are shown in fig.4. All known resonances, $a_2(1320)$ (D-wave), $a_1(1260)$ (D-wave), $\pi_2(1670)$ in the two decay channels ρp (P and F wave) and $f_2(1270\pi)$ (S and D wave), are correctly reproduced at the right mass values, as well as the additional exotic signal.

The second feasibility study is based on data already acquired by the CLAS experiment at 6 GeV. By studying the $\gamma p \rightarrow \pi^+ \pi^- \pi^0 p$ benchmark reaction for the ω decay in three pions, the result has been projected on the CLAS12 acceptance and fitted. In this case it has been observed that the result is stable against the acceptance corrections, demonstrating that the PWA will be feasible for the CLAS12 experiment.

Currently a new analysis framework is being set up by an international community involving

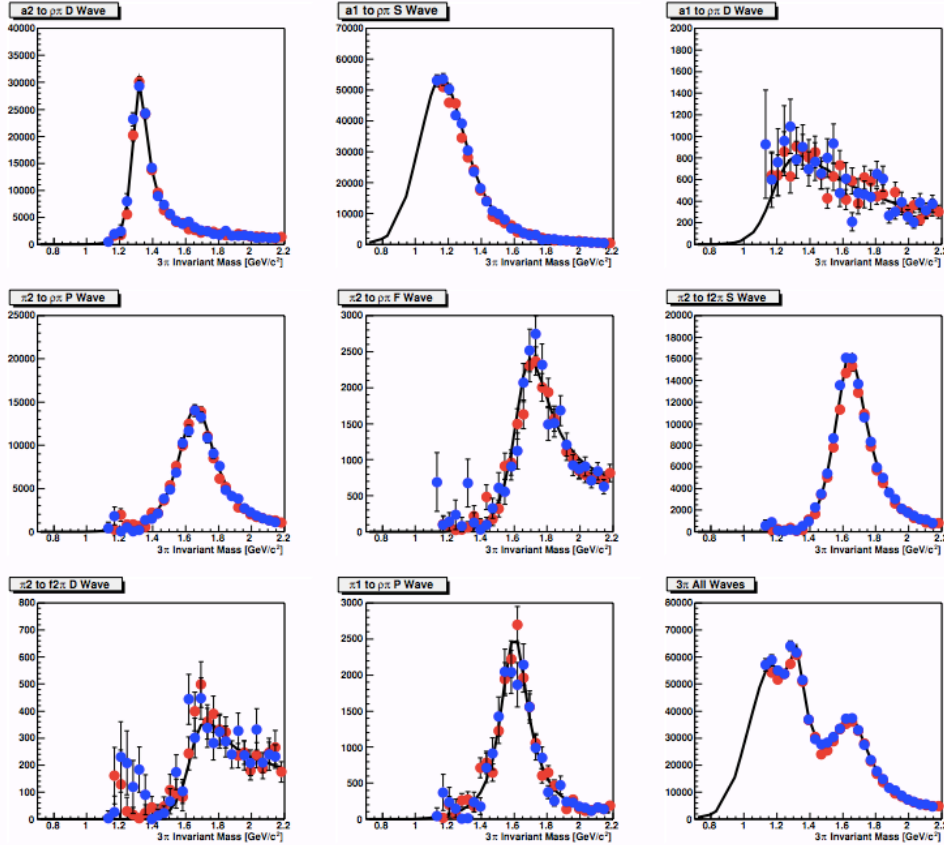


Figure 4: (Color online) The 8 isobar channels in the $\gamma p \rightarrow \pi^+ \pi^- \pi^0 n$ and the hybrid contribution shown in the central pad. The last pad on the bottom row corresponds to the 3π intensity. The different colors points are the fit results for pseudo-data selected in the two bins centered at $t = 0.2$ (GeV/c^2) (0.25 (MeV/c) 2 wide, blue points) and $t = 0.5$ (GeV/c^2) (1 (MeV/c) 2 wide, red points). The partial wave are represented by the black solid lines.

theoretical and experimental physicists experts in hadron spectroscopy. The mission of such community, gathered in the Haspect network, is to establish a common and widely accepted analysis framework which allows to univocally identify a hybrid contribution in data that will be acquired in the next generation experiments with an unprecedented statistics. Such international network is involved not only in the development of new theoretical models to perform data analysis, but also in the development of analysis tools based on advanced statistical methods to extract signals from huge statistics.

5. Summary and Conclusions

The search of exotic hybrid mesons plays a fundamental role for our understanding of the hadron mass nature and the confinement mechanism thanks to the contribution to the final J^{PC} configuration of explicit gluonic degrees of freedom. The comprehensive meson spectroscopy program deployed for the CLAS12 experiment at Jefferson Laboratory presents the hybrid meson states search in the photoproduction reactions as one of the main task. The high intensity and linearly polarized quasi-real photon beam obtained by tagging scattered electrons at small angles by the Forward Tagger apparatus, together with excellent resolution, the close to 4π acceptance and the good particle identification of the experimental apparatus, make CLAS12 a privileged observation point for the hybrid meson search. For the hybrid meson quest it is mandatory to establish a common analysis framework within the experimental and theoretical community, in order to share procedures to search for new physics. Currently the Haspect network mission is to develop such analysis framework in order to be ready for the high-statistics data collected by the next-generation experiments.

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